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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**A COST-EFFECTIVENESS ANALYSIS OF TACTICAL
SATELLITES, HIGH-ALTITUDE LONG-ENDURANCE AIRSHIPS,
AND HIGH AND MEDIUM ALTITUDE UNMANNED AERIAL
SYSTEMS FOR ISR AND COMMUNICATION MISSIONS**

by

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September 2008

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ALTITUDE UNMANNED AERIAL SYSTEMS FOR ISR AND COMMUNICATION
MISSIONS**

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ABSTRACT

Before 1991, the United States military's demand for additional communications bandwidth and timely intelligence was rising rapidly. Since then, with the advent of the Global War on Terrorism, it has increased substantially. To address this growing need, the Department of Defense has focused its acquisition and procurement efforts on obtaining new communications and intelligence, surveillance, and reconnaissance (ISR) platforms that can help lessen shortfalls and possibly exploit new, untapped resources.

Recently, there has been an increasing focus on new technology, such as tactical satellites or high-altitude long-endurance airships, as a way to increase communications and intelligence collection capacities. Likewise, advances in the capabilities of medium-altitude and high-altitude unmanned aerial systems have resulted in a more prominent role for them on today's battlefield. Each of these vehicles has a unique niche in today's military, but the increasing capabilities of each are beginning to create some overlap in their uses.

This study will conduct a cost-effectiveness analysis on these systems for use as a persistent communications and ISR platform. In particular, it will measure the effectiveness of each for comparison, and will offer possibilities to increase the overall effective use of the three together to maximize performance and cost.

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TABLE OF CONTENTS

| | | |
|------|--|----|
| I. | INTRODUCTION..... | 1 |
| A. | THESIS STATEMENT..... | 1 |
| B. | BACKGROUND..... | 1 |
| 1. | The Search for a New Solution..... | 1 |
| 2. | The Need for an Analysis of Alternatives..... | 3 |
| C. | PURPOSE..... | 7 |
| D. | SCOPE..... | 7 |
| E. | METHODOLOGY..... | 7 |
| II. | BACKGROUND..... | 9 |
| A. | UNMANNED AIRCRAFT SYSTEMS..... | 10 |
| 1. | History..... | 10 |
| 2. | Current Capabilities..... | 11 |
| a. | <i>Advantages</i> | 13 |
| b. | <i>Disadvantages</i> | 14 |
| 3. | Systems Selected..... | 16 |
| a. | <i>U.S. Army Sky Warrior</i> | 16 |
| b. | <i>Global Hawk</i> | 18 |
| B. | HIGH-ALTITUDE LONG-ENDURANCE AIRSHIPS..... | 19 |
| 1. | History..... | 19 |
| 2. | Current Capabilities..... | 19 |
| a. | <i>Advantages</i> | 22 |
| b. | <i>Disadvantages</i> | 24 |
| 3. | System Selected..... | 25 |
| C. | SMALL SATELLITES..... | 27 |
| 1. | History..... | 27 |
| 2. | Current Capabilities..... | 28 |
| a. | <i>Advantages</i> | 29 |
| b. | <i>Disadvantages</i> | 35 |
| 3. | Systems Selected..... | 36 |
| III. | ANALYSIS..... | 39 |
| A. | PURPOSE AND FOCUS..... | 39 |
| B. | ANALYSIS TYPE..... | 41 |
| C. | ANALYSIS APPROACH..... | 42 |
| 1. | Decision Science Approach..... | 43 |
| 2. | Economics Approach..... | 44 |
| D. | ANALYSIS PROCESS..... | 45 |
| E. | DETERMINING MEASURES OF EFFECTIVENESS (MOE)..... | 46 |
| 1. | MOE Attributes..... | 46 |
| 2. | Chosen MOEs/Definitions..... | 48 |
| a. | <i>Responsiveness</i> | 48 |
| b. | <i>Access</i> | 48 |

| | | | |
|----|----|---|----|
| | c. | Coverage..... | 48 |
| | d. | Endurance | 48 |
| | e. | Flexibility | 49 |
| 3. | | An Explanation of the Selected MOEs | 49 |
| 4. | | Explored and Rejected MOE's | 51 |
| F. | | ANALYSIS METHODOLOGY | 52 |
| 1. | | The Analytic Hierarchy Process | 52 |
| 2. | | Pairwise Comparison of MOEs..... | 54 |
| 3. | | Pairwise Comparison Survey | 55 |
| 4. | | The Analytical Hierarchy Process and Consistency | 58 |
| 5. | | Applying the Analytical Hierarchy Process to Attain MOE Weights..... | 61 |
| G. | | PLATFORM CAPABILITY ASSESSMENT | 64 |
| 1. | | Assumptions | 64 |
| | a. | ORS is a Functional Program | 64 |
| | b. | Pre-positioned Forces | 64 |
| | c. | No Assets are Held in Reserve | 65 |
| | d. | Platforms Must Move..... | 65 |
| | e. | Platform Dynamics and Limitations Apply to Each Scenario..... | 65 |
| | f. | Only the Scenario at Hand is Evaluated..... | 66 |
| | g. | Only Single Platform Comparisons | 66 |
| 2. | | Platform Responsiveness Qualitative Assessment..... | 67 |
| | a. | Tactical Satellites..... | 67 |
| | b. | High Altitude Airships | 68 |
| | c. | High Altitude UAS | 69 |
| | d. | Medium Altitude UAS..... | 69 |
| | e. | Considerations | 69 |
| 3. | | Platform Responsiveness Quantitative Assessment | 70 |
| 4. | | Platform Responsiveness AHP Results..... | 74 |
| 5. | | Platform Access Qualitative Assessment | 75 |
| | a. | Tactical Satellites..... | 75 |
| | b. | High Altitude Airships | 76 |
| | c. | High Altitude UAS | 76 |
| | d. | Medium Altitude UAS..... | 77 |
| | e. | Considerations | 77 |
| 6. | | Platform Access Quantitative Assessment..... | 78 |
| 7. | | Platform Access AHP Results | 81 |
| 8. | | Platform Coverage Qualitative Assessment..... | 81 |
| | a. | Tactical Satellites..... | 82 |
| | b. | High Altitude Airships | 82 |
| | c. | High Altitude UAS | 83 |
| | d. | Medium Altitude UAS..... | 83 |
| | e. | Considerations | 83 |
| 9. | | Platform Coverage Quantitative Assessment | 84 |

| | | |
|-----|---|-----|
| 10. | Platform Coverage AHP Results | 84 |
| 11. | Platform Endurance Qualitative Assessment | 86 |
| a. | <i>Tactical Satellites</i> | 86 |
| b. | <i>High Altitude Airships</i> | 86 |
| c. | <i>High Altitude UAS</i> | 86 |
| d. | <i>Medium Altitude UAS</i> | 87 |
| e. | <i>Considerations</i> | 87 |
| 12. | Platform Endurance Quantitative Assessment | 87 |
| 13. | Platform Endurance AHP Results | 89 |
| 14. | Platform Flexibility Qualitative Assessment | 90 |
| a. | <i>Tactical Satellites</i> | 90 |
| b. | <i>High Altitude Airships</i> | 90 |
| c. | <i>High Altitude UAS</i> | 90 |
| d. | <i>Medium Altitude UAS</i> | 91 |
| e. | <i>Considerations</i> | 91 |
| 15. | Platform Flexibility Quantitative Assessment..... | 91 |
| 16. | Platform Flexibility AHP Results | 93 |
| H. | COMBINING RELATIVE WEIGHTS WITH PLATFORM ANALYSIS | 94 |
| I. | CHAPTER SUMMARY..... | 100 |
| IV. | CONCLUSIONS..... | 101 |
| A. | DETERMINING COST ALTERNATIVES | 101 |
| 1. | All TacSats | 101 |
| 2. | All HAAs | 103 |
| 3. | All High-Altitude UAS | 104 |
| 4. | All Medium-Altitude UAS..... | 104 |
| 5. | Optimized Mix for Scenario A (Most Dangerous Course of Action)..... | 106 |
| 6. | Optimized Mix for Scenario B | 107 |
| 7. | Optimized Mix for Scenario C (Most Likely Course of Action) | 108 |
| 8. | Mix for Evenly Weighted Scenarios | 110 |
| 9. | Mix for Scenario A Weighted the Highest..... | 111 |
| 10. | Mix for Scenario B Weighted the Highest..... | 113 |
| 11. | Mix for Scenario C Weighted the Highest..... | 114 |
| 12. | Equal Investment in Platforms for Budget of \$9.6 Billion | 116 |
| 13. | Equal Investment in Platforms for Budget of \$4.8 Billion | 117 |
| 14. | Equal Investment in Platforms for Budget of \$1 Billion ... | 119 |
| B. | EVALUATION OF ALTERNATIVES..... | 121 |
| C. | HOW CHANGES IN THE MOES COULD IMPACT THE STUDY | 127 |
| D. | HOW CHANGES IN THE SURVEY AUDIENCE COULD IMPACT THE STUDY | 128 |
| E. | AREAS FOR FURTHER STUDY AND ANALYSIS | 129 |
| F. | SUMMARY | 131 |
| | APPENDIX A: PLATFORM MOE PROS/CONS | 133 |

| | |
|---|-----|
| APPENDIX B: PAIR-WISE COMPARISON SURVEY..... | 137 |
| APPENDIX C: PLATFORM PARAMETRIC COMPARISON TABLE..... | 141 |
| APPENDIX D: COVERAGE CALCULATION TABLE..... | 143 |
| APPENDIX E: ACCESS CALCULATION TABLE | 145 |
| APPENDIX F: SURVEY DATABASE..... | 147 |
| APPENDIX G: PLATFORM EFFECTIVENESS SCORES | 149 |
| LIST OF REFERENCES..... | 155 |
| INITIAL DISTRIBUTION LIST | 165 |

LIST OF FIGURES

| | | |
|------------|---|----|
| Figure 1. | U.S. Army Sky Warrior UAV (MQ-1C) | 16 |
| Figure 2. | Ground coverage area of a HALE Airship at 65,000 ft | 23 |
| Figure 3. | Lockheed Martin HAA..... | 27 |
| Figure 4. | TacSat-2 | 33 |
| Figure 5. | TacSat-4 CONOPS | 34 |
| Figure 6. | Space Modernization Strategy | 40 |
| Figure 7. | Pillars of the Decision Making Process..... | 43 |
| Figure 8. | Systems Engineering Analysis Process | 45 |
| Figure 9. | Hierarchy Model | 53 |
| Figure 10. | MOE Preference Scale..... | 57 |
| Figure 11. | Reciprocal Matrix of Pairwise Comparisons | 57 |
| Figure 12. | Corresponding Eigen Vectors from Reciprocal Matrix..... | 57 |
| Figure 13. | Principle Eigen Vector from Reciprocal Matrix | 58 |
| Figure 14. | Normalized Principle Eigen Vector | 58 |
| Figure 15. | Corresponding Eigen Value from the Reciprocal Matrix..... | 59 |
| Figure 16. | Principle Eigen Value | 59 |
| Figure 17. | Consistency Index | 60 |
| Figure 18. | Random Consistency Index..... | 60 |
| Figure 19. | Consistency Ratio Calculation | 60 |
| Figure 20. | MOE Survey Results for Scenario A..... | 62 |
| Figure 21. | Scenario A MOE Weights Based On Survey Results | 62 |
| Figure 22. | MOE Survey Results for Scenario B..... | 62 |
| Figure 23. | Scenario B MOE Weights Based on Survey Results..... | 63 |
| Figure 24. | MOE Survey Results for Scenario C | 63 |
| Figure 25. | Scenario C MOE Weights Based on Survey Results..... | 63 |
| Figure 26. | Platform AHP Results for Responsiveness in Scenario A | 74 |
| Figure 27. | Platform AHP Results for Responsiveness in Scenario B | 75 |
| Figure 28. | Platform AHP Results for Responsiveness in Scenario C | 75 |
| Figure 29. | Sensor Footprint Radius Diagram | 79 |
| Figure 30. | Access Measurement | 80 |
| Figure 31. | Platform AHP Results for Access in Scenario A | 81 |
| Figure 32. | Platform AHP Results for Access in Scenario B & C | 81 |
| Figure 33. | Platform AHP Results for Coverage in Scenario A | 85 |
| Figure 34. | Platform AHP Results for Coverage in Scenario B..... | 85 |
| Figure 35. | Platform AHP Results for Coverage in Scenario C..... | 85 |
| Figure 36. | Platform AHP Results for Endurance in Scenario A | 89 |
| Figure 37. | Platform AHP Results for Endurance in Scenario B | 89 |
| Figure 38. | Platform AHP Results for Endurance in Scenario C | 90 |
| Figure 39. | Platform AHP Results for Flexibility in Scenario A..... | 93 |
| Figure 40. | Platform AHP Results for Flexibility in Scenario B..... | 93 |
| Figure 41. | Platform AHP Results for Flexibility in Scenario C..... | 94 |
| Figure 42. | Final Platform Scores for Scenario A..... | 95 |

| | | |
|------------|---|-----|
| Figure 43. | Final Platform Scores for Scenario B..... | 96 |
| Figure 44. | Final Platform Scores for Scenario C | 96 |
| Figure 45. | Platform Scores With All Scenarios Weighted Evenly | 98 |
| Figure 46. | Overall Platform Scores with Scenario A Weighted Highest..... | 98 |
| Figure 47. | Overall Platform Scores with Scenario B Weighted Highest..... | 99 |
| Figure 48. | Platform Scores with Scenario C Weighted Highest..... | 99 |
| Figure 49. | Alternative 1 and 2 Effectiveness Score | 102 |
| Figure 50. | Alternative 3 Effectiveness Score | 103 |
| Figure 51. | Alternative 4 Effectiveness Score | 104 |
| Figure 52. | Alternative 5 Effectiveness Score | 105 |
| Figure 53. | Alternative 6 Effectiveness Score | 107 |
| Figure 54. | Alternative 7 Effectiveness Score | 108 |
| Figure 55. | Alternative 8 Effectiveness Score | 110 |
| Figure 56. | Alternative 9 Effectiveness Score | 111 |
| Figure 57. | Alternative 10 Effectiveness Score | 113 |
| Figure 58. | Alternative 11 Effectiveness Score | 114 |
| Figure 59. | Alternative 12 Effectiveness Score | 116 |
| Figure 60. | Alternative 13 Effectiveness Score | 117 |
| Figure 61. | Alternative 14 Effectiveness Score | 119 |
| Figure 62. | Alternative 15 Effectiveness Score | 120 |
| Figure 63. | Effectiveness Score Comparison of Alternatives | 122 |

LIST OF TABLES

| | | |
|-----------|---|----|
| Table 1. | HAA Issues and Risks | 24 |
| Table 2. | Alternative Numbers | 67 |
| Table 3. | Distance Table | 71 |
| Table 4. | Quantitative Responsiveness Assessment..... | 72 |
| Table 5. | Determination of Period and Revisit Time for LEO Platform..... | 73 |
| Table 6. | Determination of Period and Revisit Time for HEO Platform | 74 |
| Table 7. | Quantitative Access Assessment | 80 |
| Table 8. | Quantitative Coverage Assessment | 84 |
| Table 9. | Quantitative Endurance Assessment..... | 88 |
| Table 10. | Flexibility Assessment Scale | 92 |
| Table 11. | Qualitative Flexibility Assessment | 92 |

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I. INTRODUCTION

. . . in each major conflict over the past decade, senior military commanders reported shortfalls in tactical space capabilities, such as those intended to provide communications and imagery data to the warfighter in theater.¹

A. THESIS STATEMENT

The current Department of Defense (DoD) investment in medium altitude, high altitude, and tactical space persistent Intelligence, Surveillance, and Reconnaissance (ISR) and communications platforms does not currently meet warfighter operational requirements.

B. BACKGROUND

1. The Search for a New Solution

In response to the increasing demand for ISR and long-range communications, the DoD is seeking out developmental capabilities to provide this support. Millions of dollars in development and acquisition funding have been expended on programs that promise commanders additional bandwidth, additional remote sensing capabilities, and can act as a network relay to sustain these requirements. Traditionally, long-haul communications, remote sensing, and other intelligence capabilities have been primarily provided by satellites designed specifically to meet the projected needs of strategic users. As demand has increased beyond those projections, the ability of the on-orbit platforms to provide the capability that users have come to expect has become an increasing challenge.

¹ GAO, Space Acquisitions: DoD Is Making Progress to Rapidly Deliver Low Cost Space Capabilities, but Challenges Remain, August 25, 2008, U.S. Government Accountability Office, July 23, 2008 <<http://www.gao.gov/new.items/d08516.pdf>>.

Historically, satellites were viewed as a strategic asset, unavailable except at the highest levels. There are many reasons why this view persisted. First, satellites are expensive and are designed to provide a specific strategic intelligence capability or fill a specific strategic communications need. The capability of these assets to provide additional intelligence to the operational or tactical user outside of fulfilling this primary strategic role may be either more than the platform could sustain or more than its primary users are willing to give. Secondly, the cost of satellite design, development, maintenance, and control precluded any idea that all users would have separate, dedicated systems optimized for their particular requirements. The limited capability of earlier versions of these assets and the viewpoint that satellites were rare and precious commodities that should be maintained solely for supporting strategic intelligence and communications requirements, led to their limited tactical availability. Therefore, in response to this increased demand the DoD has continued to seek out and develop affordable alternatives for remote sensing and communications needs.

An early alternative used to improve the remote sensing and communications was the adaptation and development of drones into unmanned aerial vehicles (UAV). Originally used as targets for ground to air defense practice, these vehicles, once adapted with sensor or communications payloads, quickly became viable alternatives to manned reconnaissance missions or new satellite payloads. Early versions of these UAVs were constrained in capabilities compared to satellites due to their limited flight duration and payloads. As technological improvements have increased the capabilities of UAVs, DoD investment in UAV development and acquisition has increased. Another platform widely used for visual reconnaissance in the early part of the 20th century was the airship. Although earlier versions were susceptible to ground munitions and were quickly replaced by reconnaissance aircraft as technology improved, newer versions of the high altitude airship have recently emerged as a viable option to provide sustained ISR and communications relay at altitudes that are often

beyond the reach of ground threats. A third alternative, involving a paradigm shift in traditional thinking is the development of cost-effective, small, tactical satellites designed to meet the needs of tactical users. Developing small tactical satellite capabilities to support the persistent remote sensing and communications needs of the military has become a major focus of technology developers across the DoD and commercial industry. Each of these alternatives (unmanned aerial vehicles, high altitude airships, and tactical satellites) has advantages and disadvantages, both in their individual capability to meet the remote sensing and communications needs of military users and in their ability to provide military users with this capability in a timely and cost-effective manner.

2. The Need for an Analysis of Alternatives

Because of the vast amount of procurement dollars being invested into each of these intelligence and communications platforms, an essential step is to conduct an analysis to determine which can provide the desired capabilities in the most cost-effective manner. Such an analysis would allow decision makers to procure the most effective platform, or combination of platforms, that would maximize the desired capabilities while minimizing acquisition and procurement costs. However, no study of this nature has been conducted to date, perhaps because each of the platforms, in the past, had been used in a particular niche that was unique to that platform (i.e., the capabilities of each were so distinct that making a comparison was unnecessary). Another potential reason that no previous studies have been conducted is the frantic pace that technology development has maintained to meet the demands of the DoD in its Global War on Terrorism (GWOT). This operational pace has compelled the DoD to utilize whatever assets were proven and demonstrated in order to satisfy military intelligence and communications needs. However, the capabilities of these three platforms have slowly started to merge to a level that makes a comparison more realistic and necessary. Technological advancements have made the payloads aboard airships and unmanned aerial vehicles comparable to what once could

only be found aboard satellites in orbit. The distinct advantage that satellites once held in their ability to provide sustained coverage of target areas has slowly diminished as technology improvements in airships and UAVs have begun to provide them with the ability to stay on station for long duration missions. Likewise, the exorbitant cost of orbiting platforms has led the Department of Defense to seek out other alternatives to alleviate the ever-growing need of users for intelligence products and communications bandwidth. Each of these factors now makes a comparison of these platforms a necessary, logical step toward maximizing effectiveness and legitimizing spending.

DoD decision makers evaluating products from competing industry providers are required to conduct standard and streamlined cost comparisons between programs. Guidance on how these comparisons are to be conducted is given by the White House Office of Management and Budget (OMB) in OMB Circular A-76, which states, “ ... an agency shall calculate, compare, and certify costs ... to determine and document a cost-effective performance decision”.² One approach to comparisons is by conducting a cost-benefit analysis (CBA). A CBA is a method of analysis developed to evaluate investment and policy issues. Using this method of analysis, decision makers identify the gains and losses from a proposal, convert these gains and losses into monetary units, and then compare them, with the ultimate goal of deciding whether the proposal is beneficial for investment.³ However, since TacSats, UAVs, and HAAs, are individually seen as viable resources for answering identified needs, these vehicles will continue to be developed and used by the DoD to meet the battlefield communications and intelligence needs. Therefore, a CBA of these systems is unnecessary. As the technological capabilities of these systems improve, so too does the likelihood that they will begin to overlap in their ability to cover mission areas that once belonged to a singular platform. As this possibility

² Whitehouse Office of Management and Budget, OMB Circular A-76 (Revised): Performance of Commercial Activities (Washington, D.C., 2003).

³ Tevfik F. Nas, Cost-benefit Analysis: Theory and Application (Thousand Oaks, Calif.: Sage Publications, 1996).

becomes more and more an actuality, an obvious question arises: "Am I using the correct balance of available platforms to achieve mission success (effectiveness) at the lowest available cost?" To answer this question, one must conduct a cost-effectiveness analysis (CEA). This type of analysis usually takes on one of two forms: a) use of a fixed monetary value with an analysis of alternatives (AoA) based on the level of benefit provided, or b) a fixed benefit level and an AoA based on the level of cost required to obtain that level of benefit.⁴

To conduct an evaluation, common ground for comparison between the three platforms must be established. Comparisons based solely on their current employment would do little to improve understanding for DoD decision makers. First, there are unique capabilities that each of these platforms has that will continue to make them the primary choice for use in that particular need. For example, UAVs can provide streaming video to users on the ground, a capability that does not currently exist with satellites. To compare these three platforms in their ability to provide streaming video would not help DoD investors decide the best investment opportunities. For comparison to be made, we must decide upon a level playing field, consisting of capabilities all three can provide (with some variations in ability), and an analysis and comparison of each.

Another requirement for this analysis is to establish a standard for effective intelligence and communications platforms and then make a comparison between our three chosen vehicles to determine how effectively each is able to provide this level of need with respect to cost. This will help us to answer the question of each platform's ability to meet these user requirements (i.e., their effectiveness) which can then be weighed against the amount of investment required to meet that requirement (i.e., cost).

Also necessary is to determine the scope of the capabilities to be compared between the three platforms. As stated earlier, each of these three

4 Edith Stokey and Richard Edition Zeckhauser, A Primer for Policy Analysis, 1st ed. (New

vehicles has unique capabilities that are specific to that platform. A comparison of the three can only be made in the areas in which they have commonality. Therefore, for the purpose of this study, two primary mission areas will be used for comparison. The first area is in the ability of each of these platforms to provide electro-optical (EO) remote sensing. EO remote sensing provides commanders with many unique decision-making options. Some of these options include the ability to see potential targets before deciding to conduct operations in the area, allowing targets to be tracked for changes to determine activity, depicting avenues of ingress or egress so that objectives may be more accurately secured, and providing commanders with views of potential targets outside the normal spectrum of visual imagery (e.g. infrared). The second area for comparison is in the ability of each platform to provide long-haul communications between remote units on. These mission areas (EO remote sensing and long haul communications) were chosen for several reasons. First, because each of these platforms has the potential to perform these missions, and there is continuing research and development into the improvement of each to provide this service. Secondly, and more importantly, we chose these areas of comparison because they represent the most common mission capabilities that are required from these types of platforms for service to military users on today's battlefield.

With these bounds established for this analysis, it is necessary then to understand the capabilities and limitations of each platform. The following chapters will focus on providing this information, together with an understanding of their ability to meet the operational needs.

C. PURPOSE

The purpose of this thesis is twofold. First, it is to capture in one place key information relevant to persistent ISR and communications platforms. Second, is to conduct a sound cost effectiveness analysis to determine the best use of future DoD research and development and procurement funds in the areas of persistent ISR and communications platforms.

D. SCOPE

This thesis will take the view of the ground forces commander and will bound its analysis to one medium altitude UAS, one high altitude UAS, one High-Altitude Long-Endurance Airship, and two tactical space representative platforms measured against the following five attributes: responsiveness, access, coverage, endurance, and flexibility.

E. METHODOLOGY

The following methodology will be used to conduct the analysis. First, the issues and mission tasks shall be determined. During this phase, representative platforms will be selected for the analysis. Next, the Measures of Effectiveness (MOEs) to assess the platforms' abilities to satisfy the mission tasks shall be developed. The Analytic Hierarchy Process (AHP) will be used to model the decision among alternatives, derive associated criteria weights and evaluate alternatives – using both quantitative and qualitative data – in support of selected scenarios.

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II. BACKGROUND

USPACOM requires pervasive and persistent surveillance to understand adversary plans and intended actions. The size of our theater and scarcity of available assets hampers opportunities to shape the environment. To improve this situation, USPACOM would welcome new resources new sensors to increase dwell and access to potential adversary territory and communications and more human intelligence. These capabilities are critical to preventing strategic or tactical surprise.

Admiral Timothy Keating, Commander, U.S. Pacific Command, before the House Armed Services Committee, 12 March 2008. ⁵

In testimony to Congress, the U.S. Combatant Commanders have expressed the urgent need for increased levels of long-range communications to reduce dependency on commercial satellite communications and to assure tactical level access to wideband communications and the need for persistent ISR capabilities to ensure more rapid tactical dissemination of critical intelligence. These capabilities have traditionally been provided by space-based assets. However, military communication satellites often cannot provide the required capacity, and our ISR assets cannot meet battlefield commanders' requirements in a timely manner, if at all. Therefore, the DoD must consider alternative methods of meeting these requirements since launching enough large space-based assets to meet all requirements is cost prohibitive. Admiral Timothy Keating, Commander, U.S. Pacific Command, captured COCOM sentiments when he stated, "surveillance is a significant requirement of ours, and the platform that satisfies the requirement is of less interest than is the overarching requirement. The requirement still exists."⁶

⁵ Statement of Admiral Timothy J. Keating on U.S. Pacific Command Posture, 12 March 2008, March 12, 2008, August 20, 2008 <http://www.shaps.hawaii.edu/security/us/2008/keating_031208.html>.

⁶ National Reconnaissance Office cancels contracts for proposed space radar project (4/4/08) -- www.GovernmentExecutive.com, July 17, 2008 <http://governmentexecutive.com/story_page.cfm?articleid=39713&ref=rellink>.

It is now widely accepted that the U.S. military reliance on space-based systems could be our Achilles heel.⁷ Therefore, in an effort to find alternative ways of meeting our information demands and to avoid disproportionate vulnerabilities of space assets, the DoD has begun to explore alternatives. Technological advances have provided a number of improvements in the capabilities of unmanned aircraft systems (UAS), the development of high-altitude long-endurance (HALE) airships, and a renewed interest in small “tactical” satellites (TacSats) brought on by the Operationally Responsive Space (ORS) initiative. Proponents of these technologies would argue that they are a cheaper and a more effective answer to identified shortfalls than is the expansion of large national communications and ISR satellite constellations. Opponents argue that these alternatives are unnecessary and a dangerous diversion of precious resources that could be better used to improve established systems like the current generation of UAS and national technical means. In truth, each of these systems has uses for which it may be the better option. Likewise, there are disadvantages inherent to each. The following sections are a synopsis of each type of platform and details on the five specific representative systems we will use in our cost effectiveness analysis.

A. UNMANNED AIRCRAFT SYSTEMS

1. History

The idea of using drones or remotely controlled aircraft has been around almost as long as manned aircraft. During World War I, unmanned aircraft were used as flying bombs, and by World War II, they were being used as flying targets or for conducting reconnaissance missions.⁸ Today these vehicles are referred to as Unmanned Aircraft Systems, or UAS, to reflect the idea that they

⁷ Scott R. Maethner, *Achilles' Heel: Space and Information Power in the 21st Century*, (2007), August 20, 2008 <www.schriever.af.mil/shared/media/document/AFD-070906-082.pdf>.

⁸ "The fly's a spy - Unmanned aircraft; Unmanned aircraft," *The Economist* 385.8553 (2007) <<http://proquest.umi.com/pqdweb?did=1376399991&Fmt=7&clientId=65345&RQT=309&VName=PQD>>.

are much more than mere drones or bomb platforms. They are used extensively in the Global War on Terrorism in a variety of missions ranging from active intelligence collection and reporting, to kinetic strikes (with armed missiles) against targets. With the success of the U.S. Air Force Predator, originally fielded in 1995, these unmanned systems have taken on new prominence as intelligence collection platforms, using a variety of new sensors and new payload technologies.

2. Current Capabilities

The current inventory of UAS is based on the mission needs identified by each of the military services. That inventory has grown from about 200 units in 2002 to nearly 6,000 units in 2008. Approximately 1,500 of those are currently serving in Iraq and Afghanistan. Army UAS in Iraq flew more than 46,450 hours in March 2008.⁹ These platforms are combat proven.

Each service has established a tiered system to classify and separate their UAS platform inventory based on their identified usage. These identification schemes are not, however, identical among the services. In general, however, Tier I systems are low altitude, long endurance in nature (currently filled by the Gnat 750, Dragon Eye, or the RQ-11B Raven B). Tier II systems are medium altitude and long endurance systems (currently filled by the MQ-1 Predator, ScanEagle, and the RQ-2 Pioneer). Tier III systems are high altitude, and long endurance in nature (currently filled by the RQ-4 Global Hawk, and the Shadow Tactical Unmanned Aircraft System).¹⁰

The current UAS capability to conduct remote sensing missions is varied and growing. Like space-based systems, a UAS can conduct imagery intelligence using a variety of electro-optical (EO) and infrared (IR) sensors to provide imagery intelligence in the form of high-resolution photography. By doing

⁹ Jeff Horne, Space Operations (Huntsville, AL 2008).

¹⁰ Glenn W. Goodman Jr, "Three Tiers," Sea Power 49.7 (2006)
<<http://proquest.umi.com/pqdweb?did=1082432511&Fmt=7&clientId=65345&RQT=309&VName=PQD>>.

so, these systems provide ground commanders with the ability to view potential target locations or objectives within a few moments of actually attacking or occupying them. However, a UAS can also provide a capability that no satellite currently can provide: real-time video feeds. Video capabilities open up the potential for unparalleled real-time target tracking, allowing commanders the ability to make decisions based on real-time target behavior. In addition, unlike tasking national assets, which is often time consuming and may be unresponsive, the real-time tasking ability of a UAS to conduct this type of mission provides the warfighter with an ability unheard of only a decade or two ago. Similar to the unique ability to task these systems, is the ability to adapt their use based on changing situations. This provides commanders with the flexibility to assess and change coverage as the situation on the battlefield dictates.

New payload technologies under development will soon provide interesting sensors for UAS that could make their role in future combat operations even more vital. By integrating sensor suites into the very skin of the aircraft, new sensor technology is working to provide future UAS platforms with the ability to provide sensing capabilities that previously were only available with overhead satellites.¹¹ Specifically, ongoing research is working toward developing sensors that would equip current UAS aircraft with a number of innovative improvements, to include multispectral and hyperspectral imagery, enhanced synthetic aperture radar technology, and light detection and ranging (LIDAR) for foliage penetration and image collection.¹²

11 David A. Fulghum, Douglas Barrie, and Robert Wall, "Sensors Vs. Airframes," *Aviation Week & Space Technology* 165.17 (2006)
<<http://proquest.umi.com/pqdweb?did=1165402831&Fmt=7&clientId=65345&RQT=309&VName=PQD>>.

12 "Emerging Sensors Technologies for Unmanned Aircraft Systems," *Military Technology* 30.5 (2006)
<<http://proquest.umi.com/pqdweb?did=1067401631&Fmt=7&clientId=65345&RQT=309&VName=PQD>>.

a. *Advantages*

Some of the advantages of unmanned aircraft have remained unchanged from their inception. Reconnaissance missions are inherently dangerous and, if compromised, can result in extreme risk to personnel involved and cause targets to “dry up” because of the lost advantage of surprise. In addition, unmanned aircraft are uniquely capable of penetrating areas that may be too dangerous for piloted aircraft. Undetected, an overhead reconnaissance platform can provide the necessary mitigation to prevent needlessly endangering pilots while still allowing military commanders a way to collect valuable battlefield intelligence. The flexibility to adapt to changes on the battlefield, which was discussed earlier, is one of the other primary advantages UAS platforms provide. Orbiting satellite intelligence platforms are much less responsive to the fluidity of the modern battlefield. Another advantage that unmanned aircraft systems hold over traditional reconnaissance techniques is that they do not have the same physiological limitations as human pilots or reconnaissance forces on the ground. An unmanned aerial system can be utilized on every mission to maximize its performance limitations to provide target coverage. Human limitations make this technique very dangerous for extended periods with manned collection platforms. Additionally, the use of UAS platforms for reconnaissance brings with it a reduced footprint within the theater of operations, and a greatly reduced support requirement. Traditional aerial surveillance and intelligence collection techniques bring with them a support infrastructure that is usually large and expensive to maintain. Support requirements of UAS platforms are usually equivalent to a small company (~82 personnel) for four UAVs.¹³

¹³ Daniel P. McCutcheon, Daniel P., McKenzie, Timothy M., and Townsend, Kelvin J., "Comparing the Utility of a Semi-Rigid Lighter-Than-Air Vehicle to a Tactical Satellite Cluster and High Endurance Unmanned Aerial Vehicles In Performing Theater Intelligence, Surveillance, and Reconnaissance," Master of Science in Systems Engineering, Air Force Institute of Technology, 2005, 73.

b. Disadvantages

There are, however, many significant disadvantages to using unmanned aircraft for intelligence collection. In order to increase endurance the sensors carried aboard UAS platforms have traditionally been small and provided limited collection capability. Although technology research in sensor development has made tremendous improvements over the last decade, and continues to show great promise for the future, smaller UAS platforms can only carry a modest payload and their EO capabilities are still not equal to that of our orbiting national systems. The flexibility of UAS platforms provides unparalleled last minute updates on target changes. However, they have never been considered a replacement system for satellite collections, with their stabilized payloads and highly sensitive and extensive collection capability. Future improvements to UAS sensor payloads potentially could change this capability, however.

Secondly, as the use of UAS platforms becomes more and more prevalent, the potential exists for these systems to interfere with or even cause potential harm to other, manned aircraft. As the use of UAS platforms has increased, and as each of the service components within the Department of Defense has increased their dependence on their use for tactical advantage, concern has grown about the safety of the extensive use of these systems in an environment that traditionally has been the exclusive domain of manned aircraft. Although established safety regulations are prescribed to prevent this type of accident, with the increased proliferation of UAS systems comes the increased potential for collisions.¹⁴ Most recently, concern over this possibility has led senior Air Force officials to push for technology that would assist UAS platforms to “see and avoid” other aerial platforms in congested airspace.¹⁵

¹⁴ The fly's a spy - Unmanned aircraft; Unmanned aircraft 99.

¹⁵ Catherine MacRae Hockmuth, "UAVs--The Next Generation," Air Force Magazine 90.2 (2007) <<http://proquest.umi.com/pqdweb?did=1275724951&Fmt=7&clientId=65345&RQT=309&VName=PQD>>.

Finally, one of the biggest drawbacks of using UAS systems is the limited endurance of these platforms compared to satellites and airships. Although this point may seem to counter the idea of the earlier comparison to aerial platforms, an unmanned aircraft will not sustain its mission endurance to comparative levels of geosynchronous orbiting assets. Therefore, for communications missions and long-term reconnaissance, an unmanned aircraft will only last as long as its fuel capacity will sustain its flight. Therefore, UAS might not be practical for these types of missions where limited gaps in coverage are a requirement for mission success. Additionally, remaining in one place to serve as a communications relay negates one of the UAS's biggest advantages – its maneuverability and flexibility. In response to the limits to its on-station time, ongoing research is working to develop increased endurance potential for future UAS systems. One area of research is the possibility of conducting aerial refueling for these systems, by automating their navigation and providing sensors to allow close approach and linkup.¹⁶ The use of this technique, however, would require the UAS platforms conducting linkup to have the ability to distinguish between background clutter and essential components such as refueling nozzles. A second area of research is in the possibility of using solar energy to provide unlimited power to extend UAS missions. An example of this is the Helios solar powered UAV being developed by NASA.¹⁷ With a duration goal of sustained flight for up to four months each voyage, this technology would utilize direct sunlight radiation to maintain power during the day and employ the use of a hydrogen fuel cell to sustain itself overnight.¹⁸ By maintaining a level circling flight at 17-20 km altitude, the UAS would be virtually geostationary. However,

16 "Automating Aerial Refuelling for UAVs," Advanced Imaging 22.1 (2007)
<<http://proquest.umi.com/pqdweb?did=1214516341&Fmt=7&clientId=65345&RQT=309&VName=PQD>>.

17 Air-Attack.com - Helios solar powered UAV, August 21, 2008 <<http://www.air-attack.com/page/17/Helios-solar-powered-UAV.html>>.

18 G. Romeo, G. Frulla, and E. Cestino, "Design of a high-altitude long-endurance solar-powered unmanned air vehicle for multi-payload and operations," Proceedings of the Institution of Mechanical Engineers 221.G2 (2007)
<<http://proquest.umi.com/pqdweb?did=1324754831&Fmt=7&clientId=65345&RQT=309&VName=PQD>>.

this technology has not yet been incorporated into the current inventory of DoD UAS platforms. The argument of lack of endurance against UAS collection platforms, therefore, remains.

3. Systems Selected



Figure 1. U.S. Army Sky Warrior UAV (MQ-1C)¹⁹

a. *U.S. Army Sky Warrior*

The U.S. Army Sky Warrior Extended Range Multi-Purpose (ERMP) UAS is a new variant of the Predator UAS produced by General Atomics. Procured as a replacement for the Hunter UAS, the Sky Warrior, designated the MQ-1C, has an increased wingspan (48.7 ft vs. 56 ft) and is powered by the Thielert Centurion Heavy Fuel Engine that runs on the same fuel as traditional aircraft and helicopters. The new heavy fuel engine makes the logistics of supporting the system much simpler in addition to gaining better engine performance at higher altitudes. Other upgrades include an automatic takeoff and landing system, and a tactical common data link. The data links will enable communications between the Sky Warrior and the ground control stations as well as interoperability with other Army aviation platforms.²⁰ Like the

¹⁹ ERMP Extended-Range Multi-Purpose UAV, August 4, 2008 <<http://www.defense-update.com/products/e/ermpUAV.htm>>.

²⁰ United States. Government Accountability Office., Defense Acquisitions: Assessments of Selected Major Weapon Programs: Report to Congressional Committees ([Washington, D.C.]: U.S. Government Accountability Office, 2008) 158, WorldCat. <http://worldcat.org>.

Predator, the Sky Warrior carries multiple payloads and has wing hard points to carry external stores including expendable sensors and weapons. Initially, the Sky Warrior will be equipped with a Multi-spectral Targeting System Electro-optical payload for day and night observation, and a Synthetic Aperture Radar (SAR) with Ground Moving Target Indication (GMTI) capability to spot moving targets. Apart from ISR missions, the Sky Warrior will provide an airborne communications relay, providing radio relay for SINCGARS FM communications networks to support forward and isolated units located ahead of the main forces, out of line-of-sight or ground communications reach. Once fielded, the Joint Tactical Radio System (JTRS) will be included in the system's standard equipment package and replace the current FM-only relay to enable the Sky Warrior to provide communications relay to EPLRS or SINCGARS networks. This service is critical to supporting blue force tracking – a service that monitors locations and status of friendly forces.²¹ Once the Warfighter Information Network – Tactical (WIN-T) battlefield network is fielded (currently estimated at around FY2014), the Sky Warrior will carry radios capable of relaying wide-band communications in support of this new system.²²

The Army plans on making the Sky-Warrior a division controlled asset as opposed to the Predator currently being a theater-controlled asset. As such, the Army plans to purchase 12 Sky-Warrior systems (there are 10 active duty army divisions). Each system comes with 12 aircraft, ground control stations, ground and air data terminals, automatic takeoff and landing systems, and ground support equipment. According to a 2008 GAO report, total program cost will be \$1.5367 billion with an average system cost being \$128.055 million.²³ As a Land Component Commander controlled asset, and a highly capable UAS, the Sky-Warrior will be used as the representative medium-altitude UAS for the purposes of this thesis.

²¹ Sky-Warrior ERMP UAV System, August 4, 2008 <<http://www.defense-update.com/products/w/warriorUAV.htm>>.

²² Frank Bayush, Telephone Interview of Frank Bayush, July 29, 2008 at 2:00 PM PST.

²³ United States. Government Accountability Office., 157.

b. Global Hawk

The U.S. Air Forces' RQ-4A Global Hawk is a high-altitude long-endurance UAS with integrated sensors and ground stations providing intelligence, surveillance, and reconnaissance capabilities. The Global Hawk was designed from inception to provide Joint Force Commanders with high-resolution, near-real-time sensor coverage of wide geographic areas. The Global Hawk, once programmed, can autonomously taxi, take-off, fly, remain on-station collecting ISR, return, and land. Ground based operators need only to monitor the UAV health and status, and make any necessary changes to flight plans or sensor collections as the mission dictates.²⁴ Six Global Hawks have been deployed in support of Operation Enduring Freedom in Afghanistan since 2002 and Operation Iraqi Freedom since 2003, accumulating over 4,300 combat flight hours.²⁵

The platform boasts an impressive array of sensors. The Global Hawk has an EO/IR camera with 0.33 m resolution in spot mode collection. It has a 1 m resolution SAR for wide-area search and large area imagery collection. It also has a GMTI with a 4-knot minimum detection velocity.²⁶ A new version of the Global Hawk (Global Hawk-B is still underdevelopment) will have improved versions of these sensors and a signals intelligence (SIGINT) payload.

Like a satellite, the Global Hawk is controlled at or above the theater level, which sometimes makes it slow to respond to the fluid nature of the battlefield. So, although its physical abilities would allow it to be highly responsive, the information lag between the tactical level and the operational/strategic level impacts its overall responsiveness. Additionally, like

²⁴ Global Hawk RQ-4A-B, August 21, 2008 <<http://www.defense-update.com/products/g/globalhawk.htm>>.

²⁵ RQ-4A/B Global Hawk High-Altitude, Long-Endurance, Unmanned Reconnaissance Aircraft Air Force Technology, August 22, 2008 <<http://www.airforce-technology.com/projects/global/>>.

²⁶ Global Hawk Integrated Sensor Suite and Ground Segment, June 28, 2006, Raytheon, August 4, 2008 <http://www.raytheon.com/capabilities/products/stellent/groups/iis/documents/content/cms04_017868.pdf>.

satellites, the reason for the control at this high level is the limited quantities of the platforms and the staggeringly high costs. According to the GAO, as of September 2007 the Global Hawk program cost was \$9.6 billion. With only 54 platforms on order (seven A models and 47 B models), this is a cost of \$178 million apiece.²⁷ Despite these obstacles, the Global Hawk has been the most successful and well established high-altitude UAS. For this reason, the Global Hawk is the representative high-altitude UAS.

B. HIGH-ALTITUDE LONG-ENDURANCE AIRSHIPS

1. History

Airships have a history dating back to the mid-1800s. Germany developed long-range zeppelins and completed over 160 trans-Atlantic passenger-carrying flights until the Hindenburg, filled with flammable hydrogen, burned while mooring in Lakehurst Naval Air Station in Manchester Township, New Jersey, on May 6, 1937. The U.S. Navy successfully operated patrol airships filled with helium for years before, during, and after World War II. Since World War II, commercial organizations such as Goodyear have successfully flown blimps for sightseeing, sports coverage, advertising, and other uses. The improvements in airship structures and operational procedures have continued to progress through the last half-century.²⁸ Their ability to hover over a point on the ground for long periods gives them many of the benefits of a geostationary satellite. However, some technical details may need to be overcome shortly as the first prototype is constructed.

2. Current Capabilities

HALE airships fill several critical shortages across the services. The successful production of airships could greatly increase the theater

²⁷ United States. Government Accountability Office., 91.

²⁸ Lewis Jamison, Isaac Porche, and Geoffrey Sommer, High-Altitude Airships For The Future Force Army (Santa Monica, CA: Rand, 2005) 3, WorldCat. <http://worldcat.org>.

communications and surveillance capabilities that will considerably improve force performance in the theater battlespace. Airships can function as surrogate satellites. In comparison to geosynchronous space-based communications assets, they offer the advantages of shorter transmission distances, resulting in increased link margins, for relaying ground-based communications. These increased link margins result in less power need to transmit information from the ground lowering your probability of communication interception and detection. Additionally, HALE airships offer shorter ranges and much longer endurance for sensor surveillance of the battlefield and acquisition of ground targets. In comparison to UAS', the HALE airships offer a better platform for communications relays due to their longer endurance, larger footprint, and payload weight capacity. For these reasons, in the next 10 years HALE airships will prove invaluable to combat operations in all theaters.

Airships, unlike aircraft, generate lift from buoyancy instead of through aerodynamics. Consequently, airships do not need to stay in motion to remain aloft. Therefore, they can loiter over a specific location on the ground as well as move to a new location when directed. In addition, airships can carry large-volume, heavy payloads. The payload mass and maximum flight altitude is proportional to the size of the airship (the HAA objective is 4000lbs vs. 1900lbs for the Global Hawk).²⁹ These characteristics make airships ideal for multiple-payload long-endurance missions.³⁰ These High-Altitude Long-Endurance (HALE) airships, unmanned lighter-than-air (LTA) vehicles, flying high above the jet-stream at 65,000-70,000 feet (approximately 20 km) in a quasi-geostationary position will shortly serve as a platform for persistent surveillance and as a communications relay. From this altitude, airships will have a 325-mile line-of-sight radius to the horizon and a relatively benign weather environment.³¹ Many

29 RQ-4A/B Global Hawk High-Altitude, Long-Endurance, Unmanned Reconnaissance Aircraft Air Force Technology.

30 Anthony Collozza and James L. Dolce, High-Altitude, Long-Endurance Airships for Coastal Surveillance Glenn Research Center, February 2005), NASA Technical Reports Server August 4, 2008.

31 SMDC Technical Center, HALL High Altitude Long Loiter Efforts, 2006), .
<http://www.smdc.army.mil/FactSheets/HALL.pdf>. August 4, 2008.

of the critical technologies such as high-strength fabrics to minimize hull weight, thin-film solar arrays for regenerative power supply, and light-weight propulsion units have matured to the point where the ability to build and operate a prototype HALE airship is now a reality.

An example of an airship currently under development is the Defense Advanced Research Projects Agency (DARPA) Integrated Sensor Is the Structure (ISIS) program. This HALE program integrates a powerful radar into the structure of the airship. Hovering 70,000 feet above ground, the ISIS would use a giant, flexible radar antenna to give, in the words of DARPA program manager Larry Correy, a "dynamic, detailed, real-time picture of all movement on or above the battlefield: friendly, neutral or enemy."³² "We will apply this technology to track people emerging from buildings of interest and follow them as they move to new locations," said DARPA's Paul Benda. "Imagine the impact it will have if ISIS tracks the movement of individuals for months. Hidden webs of connections between people and facilities will be revealed."³³ ISIS would be CONUS based and deploy to an operational theater for up to a year. ISIS will use a large aperture size instead of high power to meet radar performance requirements. This approach exploits the platform's size and conforms to the platform's limitations on weight and power. Major technical challenges are the development of ultra-lightweight antennas, antenna calibration technologies, power systems, station keeping approaches, and airships that support extremely large antennas.³⁴ With the problems experience by the Space Radar program, ISIS would provide Space Radar-like theater level capability for much less.

The U.S. Army Space and Missile Defense Command/U.S. Army Forces Strategic Command (SMDC/ARSTRAT) has taken the lead in managing the HiSentinel program. On November 8, 2005, a team led by Southwest Research

³² Darpa's Far-Out Dreams on Display, March 15, 2004, Wired, August 5, 2008
<<http://www.wired.com/science/discoveries/news/2004/03/62646>>.

³³ Shachtman.

³⁴ Integrated Sensor Is Structure (ISIS), DARPA Microsystems Technology Office, August 5, 2008
<<http://www.darpa.mil/mto/programs/isis/index.html>>.

Institute (SwRI) successfully demonstrated powered flight of the HiSentinel stratospheric airship at an altitude of 74,000 feet. The development team of Aerostar International, the Air Force Research Laboratory (AFRL), and SwRI launched the airship from Roswell, N.M., for a five-hour technology demonstration flight. The 146-foot-long (44.5 m) airship carried a 60-pound (27 kg) equipment pod and propulsion system when it became only the second airship in history to achieve powered flight in the stratosphere.³⁵ Designed for launch from remote sites, these airships do not require large hangars or special facilities. The objective HiSentinel will be capable of 200lb/1000W payload at 67,000 feet for 30 days.³⁶ Unlike most stratospheric airship concepts, HiSentinel is launched flaccid with the hull only partially inflated with helium. As the airship rises, the helium expands until it completely inflates the hull to the rigid aerodynamic shape required for operation.

a. Advantages

HALE airships are an ideal platform for persistent ground surveillance and communications relays. However, there are a number of other potential missions suggested for HALE airships. These include: broadcast communications, missile warning, airspace surveillance and control, maritime surveillance and control, aerial and ground reconnaissance, surveillance, and target acquisition (RSTA), fires coordination, position/navigation, weather monitoring, battlespace environmental monitoring, electronic countermeasures, air defense (AD)/cruise missile defense (CMD)/tactical missile defense (TMD) weapons platform, and air-to-ground weapons platform.³⁷

Airships can function as surrogate satellites and offers the advantage of ranges shorter than those of satellite sensors for surveillance of the battlefield and acquisition of ground targets and shorter transmission distances

³⁵ Raven Industries Announces Five-Hour Flight Of 'HiSentinel' Powered Stratospheric Airship, August 4, 2008 <<http://www.spacedaily.com/news/uav-05zzzzzr.html>>.

³⁶ SMDC Technical Center.

for relaying ground-based communications. The persistent surveillance from a fixed position by airships, in contrast to periodic snapshots from the moving platforms that satellites provide, furnishes two long-needed changes to military surveillance. These changes will allow continuous collection and comparison analysis over time of terrain covered by different sensors, such as infrared (IR), electro-optical (EO), and hyper-spectral imagery (HSI). Comparisons can highlight physical changes like freshly turned dirt along a roadway where improvised explosive devices (IEDs) have been emplaced or new buildings in a desolate and unpopulated area that may indicate the construction of a new terrorist training camp.³⁸ Additionally, with a 325-mile line-of-sight radius, one airship can potentially be used for surveillance over an area the size of Afghanistan (Figure 2).



Figure 2. Ground coverage area of a HALE Airship at 65,000 ft ³⁹

³⁷ Jamison, Porche, and Sommer, 15.

³⁸ Jamison, Porche, and Sommer, 15.

³⁹ Jamison, Porche, and Sommer, 19.

Across the services, there is an increasing demand for overhead communications capacity. However, the exclusive use of military or commercial SATCOM will not be available to meet all of the services connectivity needs, and HALE airships are being considered as an optional surrogate, which will be much more cost-effective once proved technically feasible.⁴⁰

In the U.S. Army, the demand is being driven because of its transition to WIN-T and the Future Combat System (FCS). Future forces will be more dispersed so extending the range of their communications will be crucial and will be very difficult via traditional line of sight methods. Currently, satellite communications (SATCOM) are being relied upon to connect these dispersed units. The objective is to integrate both airships and satellites into a multilayered network of terrestrial-, air-, and space-based retransmission nodes.

b. Disadvantages

Disadvantages of HALE airships include areas of technical and operational risk, highlighted in Table 1 below.

HAA Issues and Risks

| Issues | Risk Management Approach |
|---|--|
| Envelope material (strength and weight) | Restrict ascent/descent conditions |
| Thermal control (superheat) | Incorporate reflective envelope |
| Helium leakage | Limit endurance; use hydrogen from fuel cells |
| Photovoltaic cells | Limit endurance |
| Fuel cells | Use Li-polymer batteries as fallback |
| Weatherability | Restrict ascent/descent conditions; improve weather prediction; provide emergency ballast dump; add sprint engine(s) |
| Survivability | Operate within own air defense envelope |
| Airspace access | Restrict ascent/descent locations and times |
| Launch/recovery | Mechanization; restrict ascent/descent locations/times |

Table 1. HAA Issues and Risks ⁴¹

⁴⁰ Jamison, Porche, and Sommer, 39.

⁴¹ Jamison, Porche, and Sommer, 32.

There is a close association between technical risk and operational utility. Recently, a great deal of progress has been made in overcoming some of the technical risks and additional risk could be managed by operational restrictions. This may include restricting the ascent and descent of the airship in adverse weather conditions. However, there will always be those risks that are unpredictable and that can result in catastrophic and unexpected system failure. These risks stem from the nature of the environment in which the vehicle operates — the effects of weather and, particularly (in the case of an airship), wind.⁴²

Airships, as with UAS's, will be vulnerable to advanced enemy air defenses. However, due to the airships' high-altitude, stationary position, and low radar and thermal cross sections only the most advanced air defense platforms will be able to detect and target them. Notwithstanding these characteristics, which make engagement by hostile air defenses more difficult, air dominance will be a requirement for full airship operations to be achieved over the battlefield.

3. System Selected

The High Altitude Airship (HAA), originally initiated by the Missile Defense Agency (MDA) as a cruise missile detection platform, is now managed by SMDC/ARSTRAT. Like the ISIS, the HAA will self-deploy from CONUS to a theater of operations and remain on-station for up to one year with the ability to station keep. The prime contractor, Lockheed Martin, is currently in the contract's third phase. The third phase of the Advanced Concept and Technology Demonstration (ACTD) program is a prototype build and flight demonstration. In this phase of the program, Lockheed Martin will build and fly a HAA prototype vehicle by the summer of 2009 in order to demonstrate launch and recovery, station keeping, and autonomous flight control characteristics and capabilities. Its utility as a mobile, retaskable, high-altitude, geostationary, long-

⁴² Jamison, Porche, and Sommer, 32.

endurance platform will span from short and long-range missile warning, surveillance and target acquisition to communications relay and weather/environmental monitoring. The capabilities of the HAA are expected to be a 4,000lb/15kW (1814 kg) payload weight and power maintained at an altitude of 70,000 feet for up to one year.⁴³ All of the payload will be carried in a pressurized, climate controlled payload bay on the bottom of the HAA. The controlled environment should enable the easy transition of sensors originally developed for high altitude UAS, such as the Global Hawk, to be migrated to the HAA platform. The Raytheon Global Hawk Integrated Sensor Suite and Ground System would make the most sense because the sensors are already optimized for the altitude for which the HAA will be flying. In addition, the sensors are platform independent so integrating them into the HAA should not be an issue. The suite includes the transmitter, receiver, integrated sensor processor, sensor electronics unit, SAR antenna, and EO/IR sensor. The sensor has a 0.33 m resolution in spot mode and a 1 m resolution in wide-area search mode. The MTI mode for vehicle velocity and geolocation has a 4-knot minimum detectable velocity. The ground segment can control up to three HAA at once.⁴⁴ Additionally, new Commercial off the Shelf (COTS) sensors should be able to quickly migrate to a HAA platform because they do not need to be ruggedized for the frequent jolts the equipment would receive on landings made by UAVs. Figure 3 below shows an artist rendition of the HAA and fulfilling some of its potential missions.

43 SMDC Technical Center.

44 Raytheon, 2.

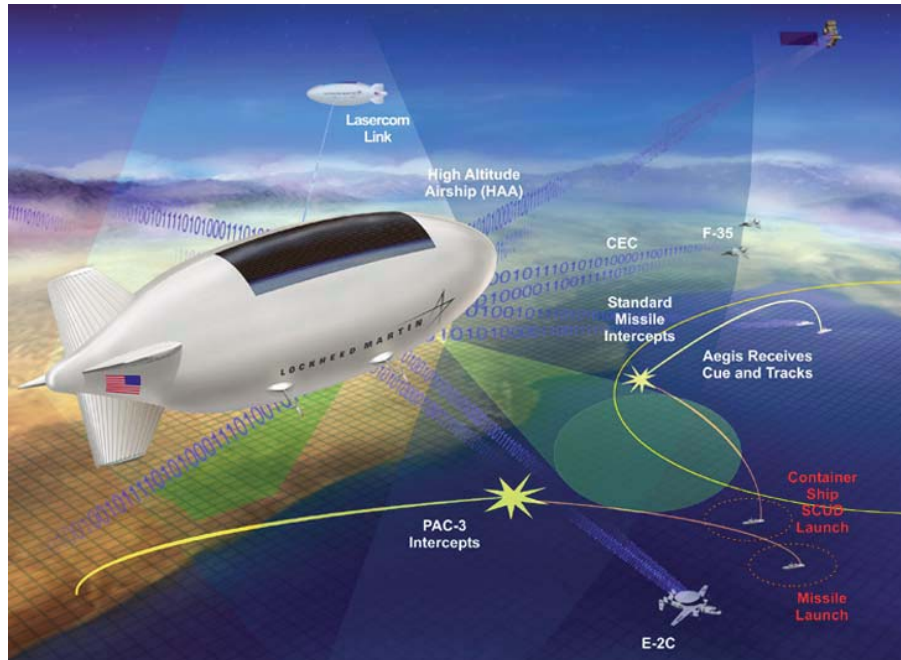


Figure 3. Lockheed Martin HAA45

For the purposes of this thesis, the HAA will be used as the representative HALE system because of its advanced state of design and predicted capabilities.

C. SMALL SATELLITES

1. History

With a diameter of 23 inches and a weight of 183 lbs, Sputnik 1 was the world's first SmallSat.⁴⁶ The United States followed that launch with a SmallSat of its own, Explorer I, a 30 lb satellite to measure the radiation belts around the earth.⁴⁷ These successful missions, and those that soon followed them, were SmallSats by necessity rather than choice. Their weight and size were small due to concerns about thrust and rocket capabilities. As satellites have evolved, they

45 High Altitude Airship (HAATM) Global Persistence for the Joint Warfighter, March 2, 2006, Lockheed Martin, August 4, 2008 <<http://www.lockheedmartin.com/data/assets/7966.pdf>>.

46 "The Sputnik," TIME October 14, 1957: August 5, 2008 <<http://www.time.com/time/magazine/article/0,9171,862778-1,00.html>>.

47 Explorer Information, August 5, 2008 <<http://history.nasa.gov/sputnik/expinfo.html>>.

have become more capable, larger and much heavier. The generally accepted definition of a SmallSat is one that weighs less than 1,000 lbs.⁴⁸ Most current generation military satellites fall into the large satellite category (over 2,000 kg). For example, Defense Support Program (DSP) missile warning satellites are over 5,000 lbs⁴⁹ while the newest communications satellite on orbit, WGS, is over 7,500 lbs.⁵⁰

2. Current Capabilities

The large size of most current DoD satellites is critical to long mission life and assurance of complex capabilities. Large solar cell areas and numerous batteries are needed to provide power to the satellite throughout its orbit and lifetime. Large buses are necessary to support the large optics of imagery satellites and large antenna of communications satellites. The complicated payloads and high-power antennas needed to convey data, however, come at the cost of long development time and high price. For example, here is a list of recent large satellite space programs and a measure of their development time from full funding to launch:

- WGS – 7 years – Nov 00 to Oct 07 ⁵¹
- AEHF – 7 years – Sep 01 to Nov 08 (projected) ⁵²
- TSAT – 11+ years – Jan 04 to Sep 15 (projected) ⁵³
- MUOS – 6 years – Sep 04 to Mar 10 (projected) ⁵⁴

48 Small Satellites Home Page - Satellite classification, Surrey Satellite Technology Limited, August 5, 2008 <http://centaur.sstl.co.uk/SSHP/sshp_classify.html>.

49 Factsheets : Defense Support Program Satellites : Defense Support Program Satellites, , August 5, 2008 <<http://www.af.mil/factsheets/factsheet.asp?id=96>>.

50 Fact Sheets : Wideband Global SATCOM Satellite : Wideband Global SATCOM Satellite, August 5, 2008 <<http://www.afspc.af.mil/library/factsheets/factsheet.asp?id=5582>>.

51 United States. Government Accountability Office., 173.

52 United States. Government Accountability Office., 39.

53 Fact Sheets : Transformational Satellite Communications System (TSAT) : Transformational Satellite Communications System (TSAT), , 8/22/2008 2008 <<http://www.losangeles.af.mil/library/factsheets/factsheet.asp?id=5332>>.

54 United States. Government Accountability Office., 143.

- SBIRS – 14+ years – Feb 95 to Nov 09 (projected) ⁵⁵
- GPS III – 7 years – Dec 07 to FY14 (projected) ⁵⁶

SmallSats, on the other hand, individually cost less and take less time to develop and launch. However, they also bring fewer capabilities to orbit. Power generation is a life-limiting factor and means the satellite can only support less complex payloads. Limited power makes hosting large imaging systems and high bandwidth communications systems on small satellites currently untenable.

a. Advantages

The generally less complex SmallSats are easier, cheaper, and faster to build and launch. Additionally, more frequent production of these smaller satellites will result in significant cost savings through economies of scale. Costs are spread out over many more units rather than having to bear the expense of maintaining a “standing army” of experts to maintain production capability for fewer larger units.⁵⁷ By building a larger number of small satellites instead of building only a few large satellites each year, the satellite industry will benefit. For the last several years, there have been concerns about the future of the military space industry due to the lack of competition and the lack of enough large contracts to “go around.” A greater requirement for small satellites will encourage new players to emerge in the industry and keep skills and expertise sharp. This leads to Learning Curve savings and more proficient and efficient producers.⁵⁸

So, the argument can certainly be made that the advantages of SmallSats are attractive. However, their small size limits their mission set. Their

⁵⁵ United States. Government Accountability Office., 153.

⁵⁶ GPS III / GPS Block III, , 8/22/2008 2008
<http://www.globalsecurity.org/space/systems/gps_3.htm>.

⁵⁷ Les Doggrell, "Operationally Responsive Space: A Vision for the Future of Military Space," Air and Space Power Journal June 1, 2006: August 5, 2008
<<http://www.airpower.maxwell.af.mil/airchronicles/apj/apj06/sum06/doggrell.html>>.

⁵⁸ The Space Review: From one, many, August 20, 2007, The Space Review, August 5, 2008
<<http://www.thespacereview.com/article/937/1>>.

small size can also be an advantage for some missions. For example, ANGELS (Autonomous Nanosatellite Guardian for Evaluating Local Space) satellites are very small satellites (around 40 lbs) that will orbit around a larger host satellite and monitor the space environment around it.⁵⁹ These satellites are being developed by the Air Force Research Lab and a \$30M contract was awarded to Orbital Sciences Corp in Nov 2007 to provide support.⁶⁰ These satellites will be able to provide the DoD with better Situational Awareness of their geosynchronous on-orbit satellites. They can monitor the satellites themselves for any obvious outward anomalies or can monitor the area around these satellites for debris or other natural or man-made threats. ANGELS is similar to a 2005 Air Force XSS-11 satellite that successfully maneuvered around and monitored satellites in LEO orbit.⁶¹

Orbital Express is a DARPA-developed program whose SmallSats are designed to “validate the technical feasibility of robotic, autonomous on-orbit refueling and reconfiguration of satellites to support a broad range of future U.S. national security and commercial space programs.”⁶² The potential of these satellites is enormous. They could potentially reduce or eliminate the life-reducing issues that face our satellites today. Most satellites run out of fuel (thus rendering attitude control useless) or have the batteries die off (there is a limit to the constant charging and recharging). Orbital Express could refuel an aging,

59 SPACE.com -- Air Force ANGELS: Satellite Escorts to Take Flight, November 30, 2005, Space.com, August 5, 2008 <http://www.space.com/business/technology/051130_airforce_angels.html>.

60 Orbital Awarded \$29.5 Million Contract For ANGELS Satellite Program By Air Force Research Laboratory, November 14, 2007, Orbital, August 5, 2008 <<http://www.orbital.com/NewsInfo/release.asp?prid=635>>.

61 David Shiga, "ANGELS to watch over US air force satellites - space-tech - 04 August 2006 - New Scientist Space," New Scientist August 4, 2006: August 5, 2008 <<http://space.newscientist.com/channel/space-tech/dn9674-angels-to-watch-over-us-air-force-satellites.html>>.

62 Orbital Express, 2007, DARPA, August 5, 2008 <<http://www.darpa.mil/orbitalexpress/>>.

but still operational, satellite or replace batteries and extend its lifetime. In March 2007, Orbital Express was launched and successfully demonstrated these capabilities.⁶³

The ANGELS and Orbital Express programs are excellent examples of how SmallSats can provide capability and fill gaps in our defense. They can reduce our vulnerabilities in space to active adversaries as well as natural degradation and anomalies. All have demonstrated technology with actual funding and contracts in place; it is obvious that this approach is being taken seriously.

There is clear military applicability to using SmallSats in the role of Space Situational Awareness and other satellite support and servicing as demonstrated by ANGELS and Orbital Express. Additionally, there is the potential that SmallSats could be used to complement and supplement the existing larger systems. Rather than replace DSP/SBIRS, a SmallSat could sit right next to it with a smaller focal plane array constantly staring at one specific volatile region. Alternatively, three SmallSats close together in the GEO belt could add more precision to the GPS constellation over a specific Area of Responsibility (similar to the Chinese navigation system). On the other hand, a SmallSat could provide low data rate communications coverage to a small sparsely used geographical area. In all of these examples, the SmallSat is not as capable as the larger constellation currently in place, but they could be used to enhance the effects and support that these systems provide.

Future applications, such as the DARPA F6 fractionated satellite program, include development of a constellation of small satellites to potentially act together as a single larger satellite. This could be accomplished by each SmallSat acting as, and having the functionality of, a larger satellite's subsystem and acting in concert to complete the mission. Such a SmallSat constellation would be easier to sustain and upgrade by having only to replace a single

⁶³ Kennedy.

SmallSat in the event of a failure. This is in contrast to replacing an entire large satellite just because of the failure of a single subsystem.⁶⁴ The military utility of such a constellation is still being analyzed.

SmallSats can also be used as a technology demonstrator. Labs and simulations are limited as to how well they can test the environmental conditions of space. Often times, a new technology's first trip to orbit is as an integral part of a multi-hundred-million-dollar satellite. Instead, SmallSats could be launched to demonstrate or develop a new technology. SmallSats could test new solar cells, thrusters, batteries, sensors, antennas, momentum systems or any number of other subsystems and payloads. "Space flown" technology is much more attractive to the acquirer of military space systems.

With "space tests" in mind, the Office of the Secretary of Defense's, Office of Force Transformation (OFT), began the Operationally Responsive Space (ORS) experimentation program in May 2003. TacSat experiments are jointly selected using an iterative process involving the Combatant Commanders and Services. Since the closure of the OFT, the ORS Office has taken the lead in the TacSat program. Today, there are four TacSats in various stages of completion. TacSat-1 was completed and ready to launch on a new Falcon-1 launch vehicle from Kwajalein Atoll.⁶⁵ However, with the failure of a Falcon-1 launch in March 2006, the flight was postponed and later cancelled. The flight was cancelled because TacSat-2 demonstrated many of the capabilities that TacSat-1 would have demonstrated if it had made it to orbit in a timely fashion.

⁶⁴ John Deutch, REPORT BY THE DCI'S SMALL SATELLITE REVIEW PANEL, trans. U.S. House of Representatives, ed. Permanent Select Committee on Intelligence (Washington D.C., 1996), . Federation of American Scientists. August 5, 2008 <<http://www.fas.org/irp/offdocs/smallsat.htm>>.

⁶⁵ John Deutch, REPORT BY THE DCI'S SMALL SATELLITE REVIEW PANEL, trans. U.S. House of Representatives, ed. Permanent Select Committee on Intelligence (Washington D.C., 1996), . Federation of American Scientists. August 5, 2008 <<http://www.fas.org/irp/offdocs/smallsat.htm>>.

The Naval Research Laboratory (NRL) has since decided to upgrade the payload in an effort to earn a manifest on a future launch once the Falcon-1 has proved it is a reliable launch vehicle.⁶⁶

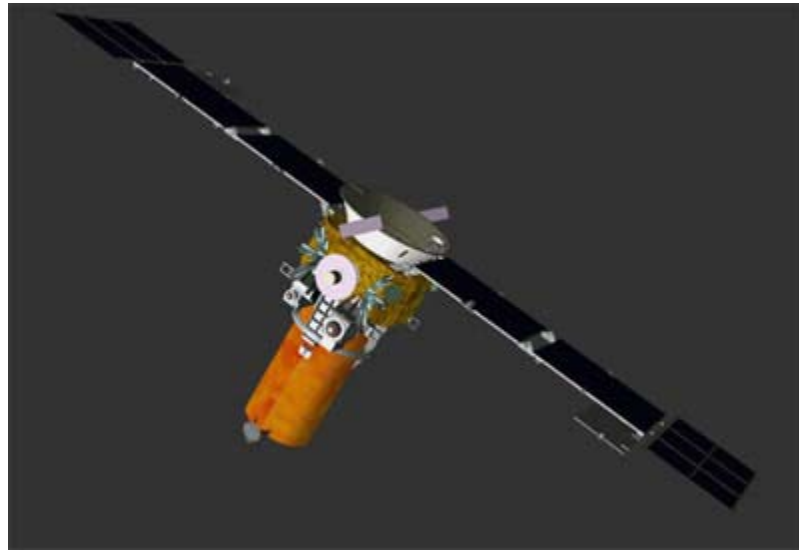


Figure 4. TacSat-2 ⁶⁷

TacSat-2 (see Figure 4), primarily sponsored by the Air Force Research Laboratory (AFRL), was an extension of the Roadrunner experiment. A spiral development process was used in the design and build of the spacecraft at a cost of \$39 million.⁶⁸ A number of experimental payload were carried into orbit on December 16, 2006, aboard a Minotaur I launch vehicle. Some of the experiments included a tactical imagery payload with approximately 1m resolution, a RF SIGINT payload, a tactical Common Data Link and UHF

⁶⁶ Pentagon Cancels TacSat-1 Mission, August 4, 2008
<http://www.space.com/spacenews/archive07/tacsat_0827.html>.

⁶⁷ Gunter's Space Page - Information on Launch vehicles, Satellites, Space Shuttle and Astronautics, August 4, 2008 <http://space.skyrocket.de/index_frame.htm?http://space.skyrocket.de/doc_sdat/tacsat-2.htm>.

⁶⁸ Space acquisitions DoD is making progress to rapidly deliver low cost space capabilities, but challenges remain : report to the Subcommittee on Strategic Forces, Committee on Armed Services, U.S. Senate., U.S. Govt. Accountability Office, 26 Aug 2008.

payloads, and a number of smaller scientific payloads.⁶⁹ After one-year of successful operation, TacSat-2 ceased operations on December 21, 2007.⁷⁰

TacSat-3 was the first mission selected by the joint community. Jointly funded by AFRL and the Army, the main payload is a hyperspectral and panchromatic imager. The Navy is also supplying a small data-exfiltration payload.⁷¹ Like TacSat-2, TacSat-3 is currently scheduled to launch in October 2008, aboard a Minotaur-I launch vehicle from the Mid-Atlantic Regional Spaceport at Wallops Island, Virginia. The satellite cost is estimated to be \$62.7 million.⁷²

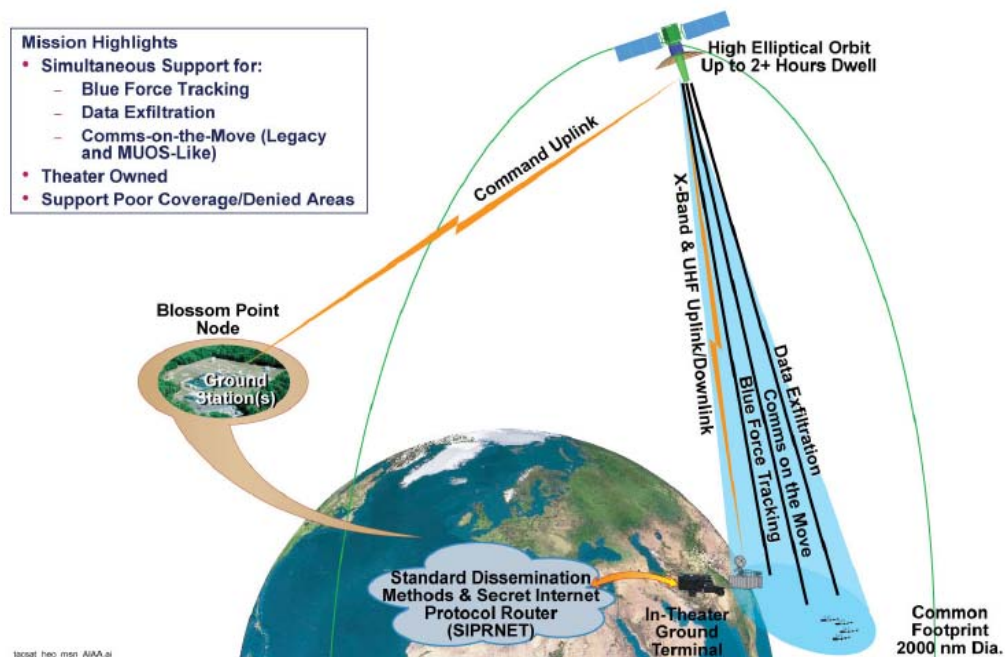


Figure 5. TacSat-4 CONOPS ⁷³

⁶⁹ Tom Doyne, et al, A TacSat and ORS Update Including TacSat-4 (Los Angeles, CA: ResponsiveSpace.com, 2006). August 4, 2008
<http://www.responsivespace.com/Papers/RS4/Papers/RS4_4006P_Hurley.pdf>.

⁷⁰ TacSat-2's Milestone Mission Advanced Responsive Space Concept, , August 4, 2008
<http://www.spacewar.com/reports/TacSat_2_Milestone_Mission_Advanced_Responsive_Space_Concept_999.html>.

⁷¹ Doyne, et al.

⁷² Government Accountability Office, 7.

⁷³ Doyne, et al.

The TacSat-4 mission, also selected by the joint community, is the first TacSat to attempt to demonstrate long-dwell capability (two+ hours per pass with about three passes per day) by using a highly elliptical orbit (see Figure 5). With this type of orbit, the satellite footprint will be approximately 2000 nautical miles (3700 km). The main payloads for the TacSat-4 spacecraft include comms-on-the-move, blue force tracking, and data exfiltration. The comms-on-the-move package supports legacy UHF users and will provide a 'MUOS-like' wideband data capability by providing tens of users data rates up to 64 kbps and possibly 256 kbps. The blue force tracking is focused on providing better service to underserved areas. Finally, the data exfiltration is a capability the Navy wants to exercise to retrieve data from buoys at sea. TacSat-4 is also a test bed for the satellite bus standardization that will be needed to make it possible to mass-produced TacSats in the future if necessary. TacSat-4 will need to be launched from a larger rocket, in this case a Minotaur IV, to get it into its highly elliptical orbit. The estimated final satellite cost is \$114 million.⁷⁴

b. Disadvantages

Despite all the advantages of small satellites, they have some serious disadvantages as well. Once in orbit it is difficult to place it into a new orbit. To changes orbits it takes a lot of fuel and satellites can only carry so much fuel with them into orbit. Once the fuel runs out, then the satellite is stuck and its orbit will decay until it falls back to Earth (assuming a small satellite in LEO or HEO). Solving this problem, with future spacecraft recently demonstrated by Orbital Express, would represent a paradigm shift in how spacecraft are operated. Satellites would be able to optimize their orbit for a new target area or move from a HEO to a LEO and back again. None of this is currently possible.

Another disadvantage is the inflexibility of the spacecraft. Once the spacecraft is launched, the payload cannot be changed. So, if the payload

⁷⁴ Government Accountability Office, 7.

malfunctions or becomes outdated, then the satellite, and your investment in it, becomes useless. The software in most satellites now can be updated, but the hardware is fixed and will deteriorate over time due to the harsh conditions in space.

When continuous, frequent contact is needed with the satellite system you are using, then it is also necessary to establish ground stations scattered across the world to maintain this communications link. Satellites transmit data to Earth with a line-of-sight radio frequency link. Therefore, if you do not have a station that can see the satellite then you cannot receive information from it. Large stations like this are expensive and represent an infrastructure cost necessary to maintain a constellation of satellites. One of the features of a tactical satellite is the desire to contact the end-user directly without this burden. Additionally, if you are lacking ground stations, then the cost of the satellite goes up because it must store the data it collects until it does pass over a ground station to download it.

Finally, another disadvantage of imaging satellites is their limited persistence over and revisit of targeted areas of interest. Although satellites have a large footprint, they do not have much time to take pictures of objects that they can see because they are traveling so fast in orbit. Additionally, to get the resolution desired by today's users, the area they can image usually gets smaller. If the resolution and the area imaged both increase, then the size of the data file becomes unmanageable and difficult to transmit back to the user.

3. Systems Selected

TacSat-2 was launched in December 2006 aboard a Minotaur-1 launch vehicle with NASA's GeneSat-1. It contained 11 experiments including an Earth Surface Imager (ESI) and SIGINT payload. The objective of the ESI was to obtain high-resolution imagery at less than 1 m Ground Sample Distance (GSD). For the purposes of this thesis, TacSat-2 will be the representative ISR SmallSat because of its successful IMINT and SIGINT mission. TacSat-4 is a satellite that

is scheduled for launch in 2009. Its mission is to provide UHF communications on the move capabilities similar to the future Mobile User Objective System (MUOS) constellation.⁷⁵ In addition, it will supplement blue force tracking capabilities in underserved locations. For the purposes of this thesis, TacSat-4 will be the representative communications SmallSat.

⁷⁵ Government Accountability Office, 7.

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III. ANALYSIS

[Current] trends point to shifts in the character and forms of future warfare. Many states will improve their conventional capabilities, and states and non-state actors alike will be able to acquire lethal capabilities. A significant trend is the blurring of what was previously thought to be distinct forms of war or conflict — conventional war, irregular challenges, terrorism, and criminality — into what can be described as hybrid challenges.⁷⁶

A. PURPOSE AND FOCUS

The purpose of the DoD's expenditure on airborne and orbiting ISR and communications platforms is well understood: the increased requirements for the warfighter to maintain continuous communications over vast distances, and the increased reliance on ISR products for operational planning. Deciding which platform (or mix of platforms) the DoD should invest in is a complex matter. The future is difficult to predict. How do we quantify the utility of these platforms under different future scenarios? The answer to this question is not easy to come by, but there is value in attempting to measure the effectiveness of these systems. By identifying cost-effective alternatives to provide to the end-user, given anticipated world events, we arm decision makers with the knowledge to invest in the right system(s). Many organizations recognize the need to address this growing demand to ensure our future capability (Figure 6).

⁷⁶ Marine Corps Vision and Strategy 2025, August 21, 2008
<<http://209.85.215.104/search?q=cache:Z9jVaFvylwAJ:www.marines.mil/units/hqmc/cmc/Documents/MCVS2025%2030%20June.pdf+Marine+Corps+Vision+and+Strategy+2025&hl=en&ct=clnk&cd=1&gl=us>>.

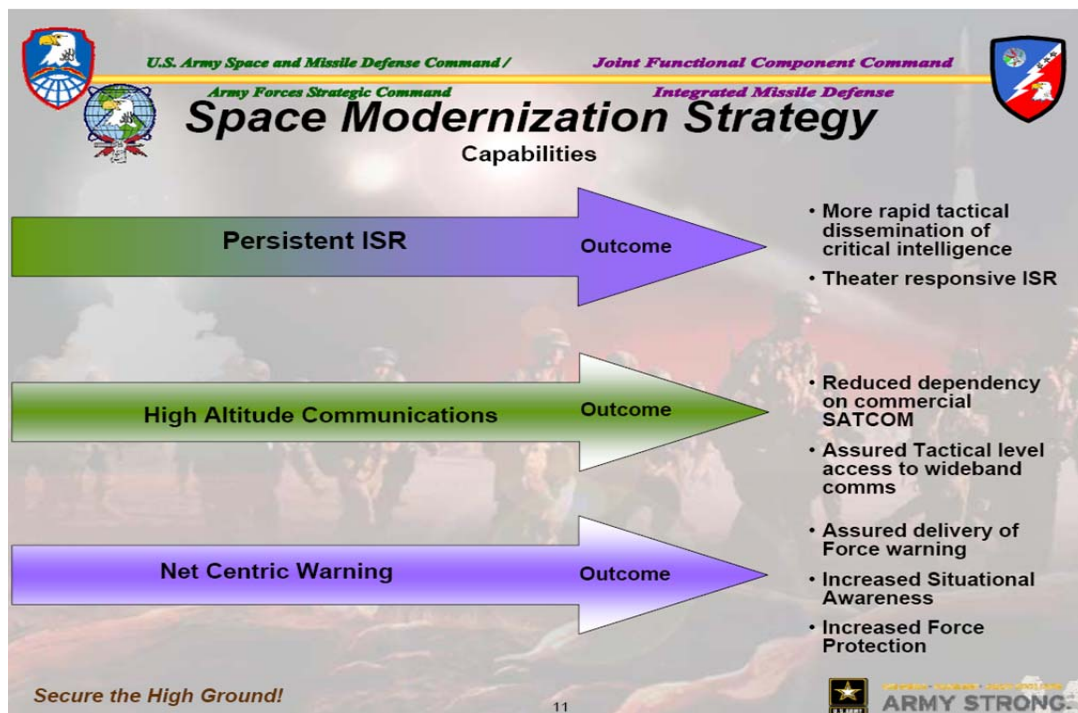


Figure 6. Space Modernization Strategy⁷⁷

The Global War on Terrorism (GWOT) is both the current DoD operational focus and is the most likely scenario for many years to come, and so was of primary consideration for our analysis.⁷⁸ This operational environment espouses a low-tech, unpredictable enemy that is often difficult to target. The real measure of how our analysis may prove beneficial is in how well it may help us to adequately invest in and deploy the optimal vehicle (or combination of vehicles) to identify, detect, or predict our enemy's next move, leading to our ability to conduct accurate target identification and targeting. In this type of operational environment successes are often difficult to ascertain and silent victories are more common. Enemy intentions may be thwarted or avoided, but to what extent may not always be known or quantifiable.⁷⁹ Concurrently, the DoD must

⁷⁷ Army Space and Missile Defense: Supporting the Warfighter, (2008) 4, August 21, 2008.

⁷⁸ Quadrennial Defense Review Report (Washington, D.C.: DoD, 2006) v-vi, June 8, 2008 <<http://www.defenselink.mil/qdr/report/Report20060203.pdf>>.

⁷⁹ The Marine Corps: "A Step Ahead..." Facing Future Challenges, Presentation ed. (Washington, D.C., 2008) Slide 7, August 27, 2008.

maintain the ability to conduct conventional military operations with peer or near-peer adversaries. To lose sight of this possibility could prove disastrous. To support either of these possibilities, decision makers must invest in technology that provides the warfighter with the most capability in every operational scenario. With a limited budget, he must decide if he will spend money on UAVs, HAAs, or TACSATs, or in some ideal combination thereof.

B. ANALYSIS TYPE

As stated earlier, a comparison of these four platforms is possible as long as the analysis is in areas they all have in common. For this reason, we chose two primary areas for comparison: electro-optical remote sensing and communications. As shown in Figure 6, ISR and communications are key components of our future space strategy for meeting warfighter needs. All three platforms in this study possess the ability to provide an enhanced capability to collect optical intelligence and to provide long-range communications to improve the operational capability and reach of the warfighter. Our initial inclination for this comparison was to conduct a cost-benefit analysis (CBA). A CBA identifies all the gains and losses from a proposal and converts them into monetary units for comparison. According to Stokey, a CBA is a five-step process:

1. Identify projects to analyze.
2. Identify all present and future impacts (both favorable and unfavorable).
3. Assign values (usually dollars) to these impacts. Register favorable impacts as benefits, unfavorable ones as costs.
4. Calculate net benefit.
5. Make choice.

However, as the author goes on to explain, the “elements of benefit-cost analysis are [used to] determine whether a project ... should be undertaken.”⁸⁰ The particular systems involved in our study are, and will continue to be, market

⁸⁰ Stokey and Zeckhauser, 136.

areas in which the DoD already has investment and interest. Therefore, a CBA of these systems is not the preferred analysis tool for comparison.

Nevertheless, it was necessary to continue to search for a way to evaluate the degree of government investment needed in these programs to determine the correct combination for maximum effectiveness. The analysis tool that assists with this situation is the cost-effectiveness analysis (CEA). A CEA still measures costs and benefits, but eliminates the need to use a common metric to measure them. According to Stokey, “a cost effectiveness analysis is applicable when (a) costs of alternative projects are identical [and] benefits need to be compared ... or (b) when benefits are identical and ... costs need to be compared.”⁸¹ Therefore, a CEA is the applicable analysis tool for our study.

C. ANALYSIS APPROACH

There are numerous directive publications and guidelines within the DoD to assist program managers in ways to determine the best alternative for identified mission needs. All of them, in some way, center on the idea that program managers must conduct a “...structured process for [evaluating] the most efficient and cost-effective method of performance for commercial activities...”⁸² Based on available information, program managers must decide where the best alternative investment lies between competing programs.

Numerous methods exist to assist in making these decisions, but all methods focus on certain core foundational truths of objective analysis, as shown in Figure 7.

⁸¹ Stokey and Zeckhauser, 154.

⁸² Whitehouse Office of Management and Budget.

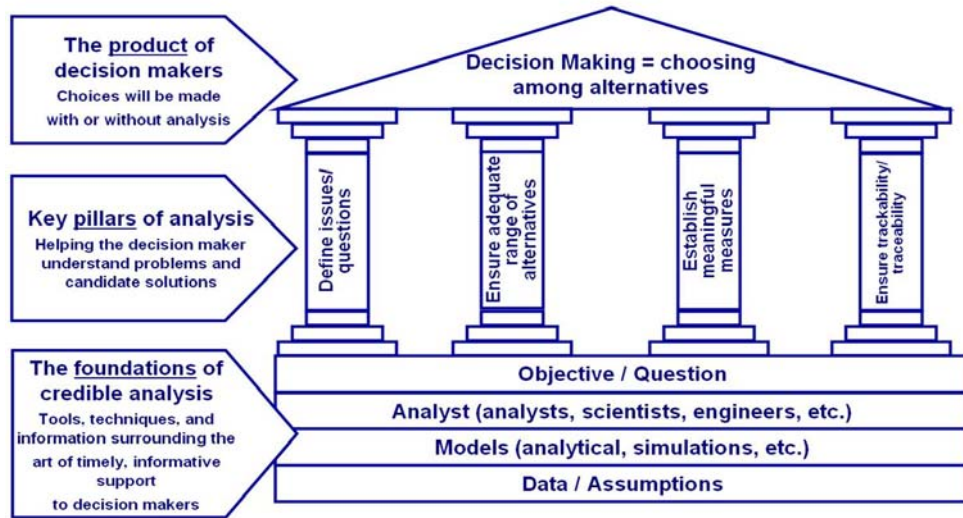


Figure 7. Pillars of the Decision Making Process.⁸³

To ensure the best possible decision, program managers are required to conduct an objective analysis that determines which investment achieves the required mission performance with regard to design, cost, risk, and schedule. Decision makers have two primary approaches to choose from to answer the problem: the decision science approach and the economics approach. Both approaches use similar tools (e.g., cost-benefit analysis, cost-effectiveness analysis, etc.) to assist decision makers. However, they differ in their view of the various alternatives. The decision science approach focuses on an analysis of alternatives (AoA) while the economics approach focuses on an evaluation of alternatives (EoA).

1. Decision Science Approach

An AoA is “...an analytical comparison of the operational effectiveness, suitability, and life-cycle cost of alternatives that satisfy established capability needs.”⁸⁴ The intent is to be quantitative, comprehensive, and objective, and to

⁸³ Modeling, Simulation, & Analysis: DoD Lessons Applied to NASA Problems, May 19, 2005, Teledyne Brown Engineering, Inc., August 4, 2008
<<http://www.aiaa.org/Participate/Uploads/Rice%20SBA.ppt>>.

⁸⁴ Defense Acquisition Guidebook, July 28, 2008
<<https://akss.dau.mil/dag/DoD5000.asp?view=document>>.

examine multiple aspects of a program's alternatives with a focus on determining the best alternative based on the understanding of technical risk, maturity, cost and price. Through the process of conducting the AoA, decision-makers establish better program understanding and insight into the facts surrounding the program and answers to some of the assumptions. In summation, the analysis must outline the relative advantages and disadvantages of the alternatives considered within the AoA.⁸⁵ The result of this analysis is intended to answer the question: "Given the alternatives, which one maximizes the best value?"

2. Economics Approach

An EoA provides an economical approach to decision making. The objective is to select the alternative that maximizes utility to the end-user with respect to an evaluation of varying budget restraints. Both techniques attempt to objectively evaluate alternatives, and both techniques use cost-effectiveness analysis (CEA) to conduct this evaluation. The primary differences between the two methods (AoA vs. EoA) are: a) where, in the process of the analysis, the CEA takes place; and b) the variables used in the analysis. In the AoA, "... the last analytical section of the AoA plan deals with the planned approach for the cost-effectiveness comparisons of the study alternatives."⁸⁶ By contrast, this is typically the first step in the EoA. The AoA approach typically measures effectiveness against cost, while the EoA approach measures both effectiveness and cost variables but applies an estimated budget to determine the impact on the CEA. This allows the decision maker to ask the question: "Could an incremental increase (or decrease) in budget result in a marked improvement (or degradation) in effectiveness?" The question becomes particularly important once real budget constraints are applied to the problem. A study of this nature can allow the decision maker to make the best investment decision in the event

⁸⁵ Mandatory Procedures for Major Defense Acquisition Programs (MDAPS) and Major Automated Information System (MAIS) Acquisition Programs, June 10, 2001, Office of The Undersecretary of Defense, September 10, 2008 <http://www.mitre.org/work/sepo/toolkits/risk/references/files/DoD5000.2R_Jun01.pdf>.

⁸⁶ Defense Acquisition Guidebook Sect 3.3.

of budget shortages (which can be quite common) or increases to determine their impact on overall capability. For the purposes of our study, we chose the economics approach. This approach allowed us to examine budget changes on the degree of mission capability that each of our alternatives could provide.

D. ANALYSIS PROCESS

To assist our analysis, we followed a process commonly used by DoD and commercial systems engineering companies and depicted in Figure 8. This analysis process assisted us in our evaluation of the alternatives for investment in ISR and communications platforms.

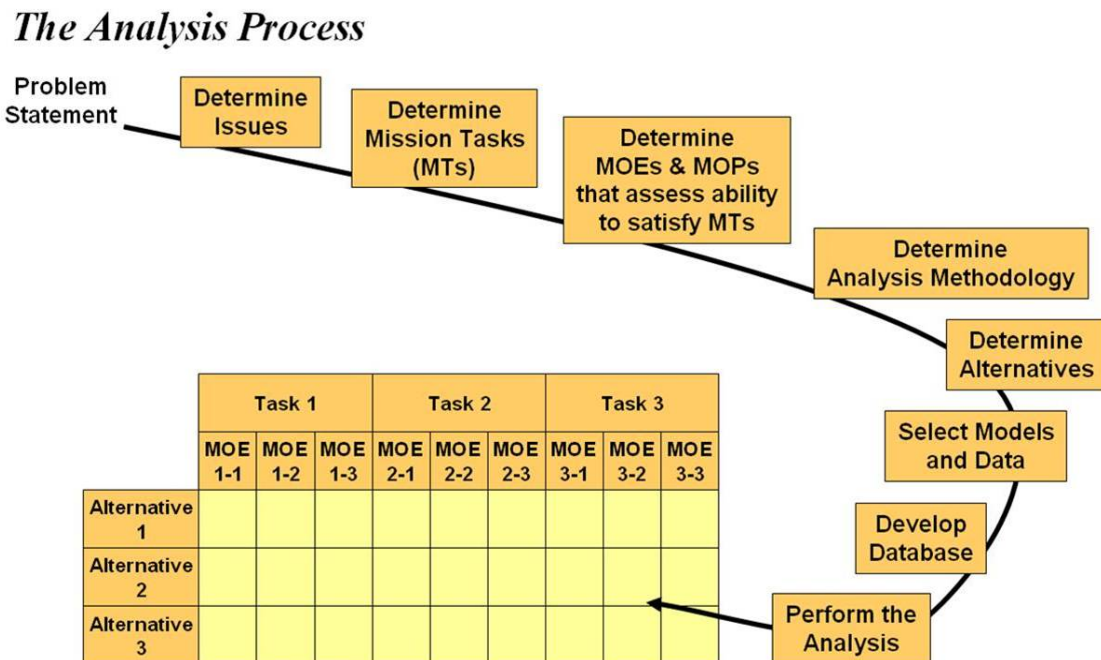


Figure 8. Systems Engineering Analysis Process⁸⁷

Previous discussion covered the first three steps of the process in detail. To reiterate, we identified 1) the increasing requirement within the DoD for persistent ISR and communications coverage; 2) the shortfall in investment in platforms to meet operational user needs; and 3) the need for an analysis to

⁸⁷ Rice, 5.

determine the best solution to meet this shortfall. Although a good model for mapping out our analysis, the model does not flow perfectly for our study. In our study, since the alternative platforms are decided, the selection of alternative combinations will take place after the development of database results. Subsequent sections discuss the outcomes of the process steps.

E. DETERMINING MEASURES OF EFFECTIVENESS (MOE)

1. MOE Attributes

There is no universally accepted answer to define an MOE. According to established policy that regulates government acquisitions, an MOE “lists the performance capabilities identified as required in the ORD (operational requirements documents)”.⁸⁸ (The ORD has since been replaced by the Capabilities Development Document.)⁸⁹ In other words, an MOE defines what the acquisition needs to be capable of doing to meet user needs. Noel Sproles attempts to expound on this understanding by explaining, “[these] standards are specific properties which any potential solution must exhibit to some extent.”⁹⁰ They are further described as “showstoppers” that are usually small in number. They are defined by the person(s) in the preeminent position to determine needs and the ability of alternatives to meet those needs (i.e., “stakeholders”), which is a key aspect of their formulation.

When selecting MOEs for our evaluation, we searched through numerous documents to find measures that all three systems had in common. Keeping in mind that an MOE “defines what is wanted rather than what must be done,” our selection focused on those measures where we could find, to the greatest degree

⁸⁸ Mandatory Procedures for Major Defense Acquisition Programs (MDAPS) and Major Automated Information System (MAIS) Acquisition Programs 127.

⁸⁹ Joint Staff / J-8 Capabilities and Acquisition Division, JCIDS Overview (Washington D.C.: Department of Defense, 2005), September 10, 2008
<http://www.dau.mil/performance_support/docs/Nov_2005_JCIDS_Overview.ppt>.

⁹⁰ Noel Sproles, "Coming to Grips with Measures of Effectiveness," System Engineering: The Journal of the International Council on Systems Engineering 3.1 (2001) Topedo Ultra July 30, 2008
<<http://torpedo.nrl.navy.mil/tu/ps/doc.html?dsn=3129308>>.

possible, quantitative objectivity (although measures with qualitative subjectivity were not eliminated). As defined, we feel the MOEs chosen for the study represent those MOEs “whose qualities were sufficient to determine if a given system meets the stakeholder’s requirement.”⁹¹

The first step is identifying the stakeholders. The analysis considered a wide audience. Recent wargames such as Schriever IV used HALE airships to support Northern Command and DHS for border security.⁹² NASA has used small satellites for various scientific experiments. However, the thesis scope states that the analysis should be from the view of the ground forces commander therefore, he is the primary stakeholder with other stakeholders considered secondary. With a combined 28 months command time in Iraq the authors have a good grasp of what is important to the ground forces commander.

Next, in order to maintain a level playing field, any MOE that obviously applied only to one platform more than to the others, and would therefore give it a significant advantage, was not considered. Each platform may perform exceptionally well in a niche area, but the goal is to find an overall best choice. Additionally, MOEs that focused solely upon specific sensors were not considered. Sensor technology advances so quickly and the field of sensors are so large that it was decided to maintain focus on the platforms, which will be around for decades, instead of on sensors which will continue to change frequently. However, some MOE’s will depend partially on a sensor type, and in instances such as this, a generic sensor with known capabilities was used for the required sensor characteristics.

91 Noel Sproles, "The Difficult Problem of Establishing Measures of Effectiveness for Command and Control: A Systems Engineering Perspective," *System Engineering: The Journal of the International Council on Systems Engineering* 4.2 (2001) *Torpedo Ultra* July 30, 2008
<<http://torpedo.nrl.navy.mil/tu/ps/doc.html?dsn=3145053>>.

92 George Luker, "Army Space @ Schriever IV," *Army Space Journal* Volume 7.Number 2 (2008)
<http://www.armyspace.army.mil/Pic_Archive/ASJ_PDFs/ASJ_VOL_7_NO_2_SPRING_2008_Article_3.pdf>.

Last, MOEs that could be evaluated with quantitative measures were used for comparison to the qualitative analysis, in order to validate qualitative analysis. In instances where quantitative analysis was not possible, fairness in evaluating the MOE was paramount.

2. Chosen MOEs/Definitions

Our MOE model represents the chosen measures for the alternatives to meet ISR and communications needs. The following definitions bound the scope of how each MOE was assessed and then used in the study.

a. Responsiveness

The ability to react to new missions in a different geographical area and begin passing the user actionable data. Additionally, it is the ability to replace the asset if lost.

b. Access

The geographic extent of what the payload can see over time – i.e. no time limit; for example, a single satellite in polar orbit has a global access area.

c. Coverage

An indication of how quickly the system can view an appropriate area of interest measured in km^2/hour .

d. Endurance

The continuous amount of time a platform can spend over the target area.

e. *Flexibility*

The ability to use the same asset to perform more than one mission simultaneously and its ability to be configured for different missions.

3. An Explanation of the Selected MOEs

Many MOEs measure multiple capabilities. One such MOE in this case is Responsiveness. Responsiveness, as defined above, measures not only the ability to react to new missions, it also is the ability to reconstitute a lost asset if required. If a platform cannot quickly respond to conditions or opportunities on a fluid battlefield then its operational use diminishes greatly. Targets of opportunity are often fleeting and the platform you are using for surveillance must react quickly to track the target until the decision is made to conduct additional tracking for intelligence purpose or to make a kinetic strike. If a platform is not capable of responsiveness, then it is probably better suited for strategic missions that do not call for sudden changes due to the fluidity of conflict. The assumption for this MOE is that ground capabilities and processes exist for expeditious movement of the data from the ground station to the user who requested the capability or product. Responsiveness is measured in hours.

Access and coverage are similar, but their distinct differences lend each attribute to be a separate MOE. Access is the ability of a platform to see or move over a piece of territory, measured in km^2 . Access takes into account threats to the operation of the platform – for example, an airborne platform does not have access to an area protected by an air defense system. Coverage is the ability to exploit the area you do have access to, measured in km^2/hour . This is a critical difference. A satellite in polar low Earth orbit has global access whereas UAS and airships do not. This means that a satellite can peer into denied territory in peacetime or before the achievement of air superiority in times of conflict. Additionally, during peacetime, airships, with their high altitude, can see a considerable distance into unfriendly countries by parking inside the borders of a friendly neighbor or by loitering in international waters off their coast. Once

access over an area is gained, coverage is the ability to exploit the access area available to you at that time by conducting ISR or communications. The ability to achieve coverage is a function of both the platform and the payload. Payload coverage is what you are after but coverage cannot occur unless you have access. The type of platform you choose will determine if you have access to the area you want to look at or if you can talk to the forces you have hidden there. Therefore, when trying to determine what the best platform is for persistent ISR and communications, access and coverage are both critical MOEs.

Endurance is the ability to spend time over a target area measured in hours. The endurance of a platform is the single most important factor in determining how many platforms you will need to maintain persistent ISR or communications over a target on the ground. If persistence is required, and you are on a budget, then you can achieve this by continuously sending up inexpensive platforms that have little endurance or you can invest in a system that costs more but has much greater endurance. If persistence were not required, assuming all other capabilities are equal, then the cheaper platform would of course be the way to proceed. However, if persistence is necessary, as stated by some COCOMs, a way to maximize endurance must be found.⁹³

Lastly, flexibility is the ability of an asset to perform more than one mission simultaneously. This MOE is, unfortunately, more qualitative than quantitative. All platforms have the ability to perform ISR and communications at the same time but not to the same degree. Some platform optimization must take place in order for that alternative to be good at either one mission or the other or risk performing poorly at each. Some platforms can perform ISR missions very well but can only perform rudimentary communications relay functions. So, in trying

93 Bryan D. Brown, GEN, Statement of General Bryan D. Brown, U.S. Army Commander United States Special Operations Command Before the House Armed Services Committee Subcommittee on Terrorism, Unconventional Threats and Capabilities on the Current Manning, Equipping, and Readiness Challenges Facing Special Operations Forces 31 January 2007, trans. U.S. House of Representatives, ed. House Armed Services Committee Subcommittee on Terrorism, Unconventional Threats and Capabilities (Washington D.C., 2007) 9, August 25, 2008 <<http://armedservices.house.gov/pdfs/TUTC013107/Brown%20testimony013107.pdf>>.

to determine how to rate the different platforms, each platform was assigned a subjective rating. On a scale of one to five, based on current or predicted capabilities, each platform was assessed while performing the ISR mission and the communications mission, in comparison to the other platforms.

4. Explored and Rejected MOEs

There were a number of possible MOEs considered but rejected for various reasons. The first rejected MOE was Data Quality/Quantity. Some of the potential measures for this MOE would have been resolution for an ISR payload, and bandwidth or number of users for a communications payload. We rejected this attribute from our analysis for two reasons. First, the majority of information on payload capability is proprietary information and/or classified. The analysis focused on publicly available information in order to reach the largest audience possible. Second, the exact payloads for some of the platforms (airships and future TacSats) are undecided, which would have led us to guess which payload the DoD would procure. Additionally, the MOE draws too much attention to the sensors when the thesis is concentrating on the platform.

The next rejected MOE was Risk. There are several elements to risk. Technology risk is not an issue because all platforms are at least in the prototype development phase. Survivability is an element of risk – the potential risk and probability of platform destruction from adversarial actions. All platforms are susceptible to shoot-down by a military near-peer. Therefore, the ability to reconstitute might be something that is valuable. However, reconstitution was very close to Responsiveness so it became a contributing factor in the platforms Responsiveness MOE. For these reasons, we decided that Risk alone was not important enough to be an independent MOE.

The last MOE considered and rejected was Cost. Cost was eliminated when it was decided that a cost-effectiveness analysis was the direction the thesis would take. For our cost-effectiveness analysis, cost is an independent

variable and therefore fixed. The analysis focused on platform effectiveness within established cost parameters to evaluate effectiveness. Therefore, Cost cannot be a MOE.

F. ANALYSIS METHODOLOGY

1. The Analytic Hierarchy Process

To assist in the analysis comparing dissimilar alternatives, we used the Analytic Hierarchy Process (AHP); a multi-criteria decision-making technique developed by Thomas L. Saaty, a Professor in the Graduate School of Business of the University of Pittsburgh. According to the author, the AHP's purpose is to provide a "process [to be] used to develop creative courses of action and evaluate their effectiveness ... [to] evaluate the impact of relevant factors in complex situations."⁹⁴ The AHP uses the notion of priority expressed in terms of ratios, because priority is applicable to both the MOEs and the alternatives. To develop these ratios, the AHP uses paired comparisons between the alternatives, and between the MOEs, to develop a model for decision makers considering all relevant factors.

⁹⁴ Thomas L. Saaty, *Decision-Making for Leaders: The Analytic Hierarchy Process for Decisions in a Complex World*, 2nd ed. ed. (Pittsburgh, PA: RWS Publications, 1990) 25.

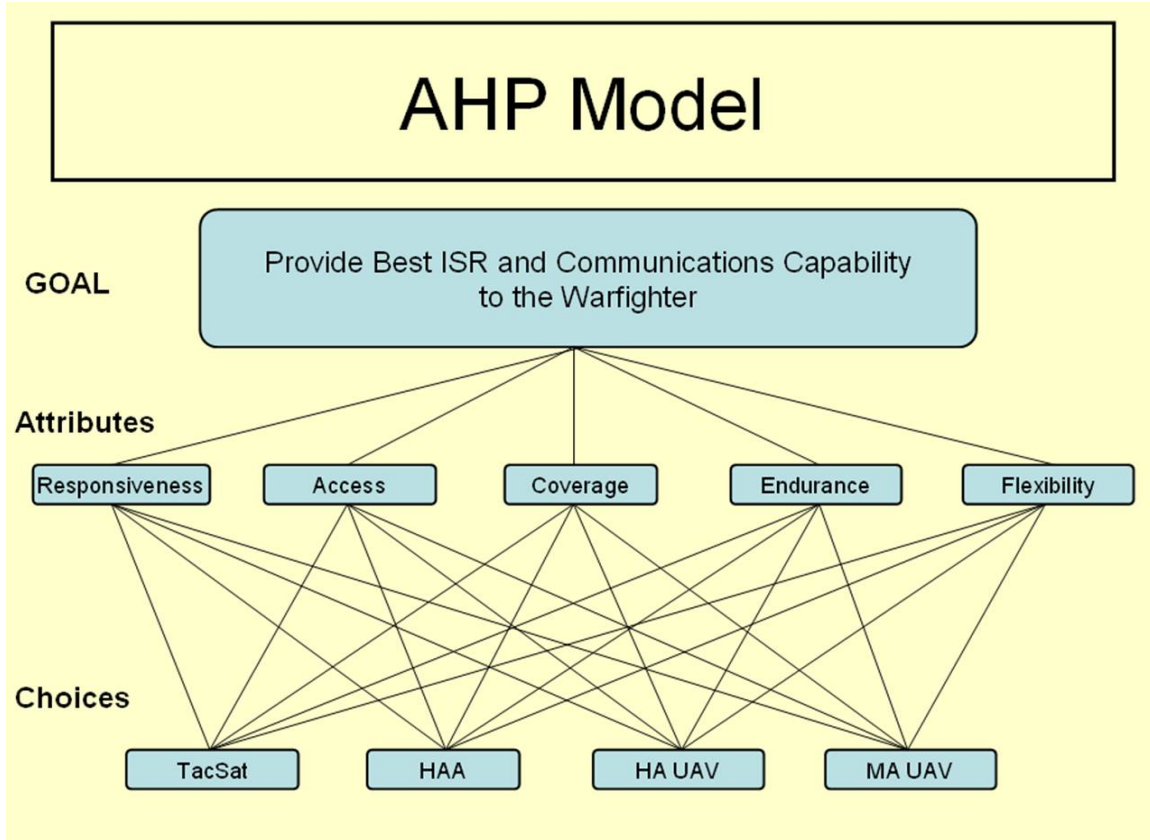


Figure 9. Hierarchy Model

The first step in the AHP is to define the problem, which our study has previously stated. The second step in the AHP is to model the problem as a hierarchy of interrelated tasks. Figure 9 gives a depiction of the AHP hierarchy model used for our thesis.⁹⁵ The top level of the model is the goal of the analysis, while the subordinate level lists the attributes or criteria that must be met to achieve the overarching goal. For a cost effectiveness analysis, these attributes are the MOEs. The bottom level of the model depicts the choices or alternatives available to the decision maker. As the figure depicts, the AHP organizes complex decisions into its various components. The AHP then analyzes these components in a pairwise comparison to develop priorities within the hierarchy.

⁹⁵ Saaty, 33.

2. Pairwise Comparison of MOEs

The next step in the AHP is to evaluate the elements of the hierarchy by comparing them to one another in pairs in order to develop a scale that captures the relative importance of each attribute. The purpose of this step is to determine the priority of these measures, from the viewpoint of the stakeholder, by converting them to a quantitative measure that falls within the set (0, 1).

The pairwise comparisons within the AHP can be either quantitative attributes that are easily measured and compared, qualitative comparisons based on the level of satisfaction or preference given as an opinion, or some combination thereof. Using the MOEs selected and defined for our analysis, our study attempted to capture the relative importance of each of them for comparison while also considering that the alternatives would yield widely varying results in their ability to meet these measures. The quantitative measurement of the alternatives in our study will be discussed later.

By measuring the relative importance of the MOEs, we can determine, under set conditions (i.e., a scenario) which measure is most desirable to the stakeholder and the impact of that preference on the remaining measures. We can also examine the impact on preference that a change in conditions may have. If, for example, you use the idea of building a racecar, your MOEs may include speed, durability, fuel consumption, and simplicity of design. If asked to rank each of these MOEs on relative importance, a panel of experts may prefer one attribute above the other and may even change their opinion based on the scenario given. For mountainous, endurance races, it may be more important that the car consume less fuel because the course does not support refueling stops. For grueling off-road races, experts may prefer durability above other attributes. The point is that one attribute often comes at the expense of others. It is, therefore, beneficial to know and understand which MOEs stakeholders hold in highest regard, so that, under established conditions, you will understand how this preference affects your evaluation of alternatives. If an alternative

outperforms the others in one attribute, and that attribute is highly preferred by stakeholders for the scenario at hand, then the weighting of attribute preferences distinguishes the alternative as the best solution. Conversely, an alternative adept in an attribute that is not highly preferred by the stakeholder may not emerge as the best choice for the solution.

3. Pairwise Comparison Survey

To derive the relative weighting values to our MOEs, we conducted a survey of professionals. The survey participants ranged from professors at the Naval Postgraduate School teaching space systems operations, to various Soldiers and Marines currently assigned to billets with direct involvement in the establishment of requirements for and the procurement of ISR platforms. The survey, shown in Appendix B, asked the participants to establish, from their perspective, the priority of importance of the selected MOEs within three selected scenarios. Scenario A was that the United States was engaged in high intensity operations without air superiority. Scenario B was that the United States was engaged in high intensity operations with air superiority. Last, Scenario C was that the United States was engaged in low intensity operations with air superiority. The scenarios were chosen to reflect the full spectrum of operations that today's warfighter must be prepared to conduct, from conventional maneuver warfare to distributed low intensity conflict.⁹⁶

The participants were asked to rank the selected MOEs within the defined scenario in order to ascertain how the perceived importance of the selected MOEs might change within the spectrum of conflict. To form a ratio scale we asked participants to evaluate the MOEs against each other and assign relative values to reflect their preferences. The fundamental scale of the comparison used the real numbers in the open interval (0, 5) which are associated with the intensity of the participant's opinion of importance or preference.

⁹⁶ The Marine Corps: "A Step Ahead..." Facing Future Challenges Slide 20.

Before analyzing the data from the survey, it is important to note that some decision scientists have criticized the use of ratio scales to arrive at a decision. One of the pitfalls often associated with analysis of varying alternatives is the artificiality of known scales of measurement (or conveniently improvised numbers) to make decisions. This often happens from the misuse of normalization. As Saaty describes:

Among the various number crunching procedures the most pernicious is that which assigns judgments to alternatives...by first selecting numbers from some arbitrary set and then normalizing them by multiplying them by a constant that is the reciprocal of their sum. [The] normalized sets now lie in the interval $[0, 1]$, no matter what scale they originally came from, and can be passed off to the uninitiated as comparable.⁹⁷

The problem compounds when the issue is a multi-criteria decision. Comparing ratio scales developed for each criterion cannot assist with a unique overall decision. To avoid this issue, Saaty recommends using ratio scales in the weighting operation to help preserve proportionality before and after normalization.

To understand how the AHP uses the pairwise comparison within the hierarchical decision tree, an explanation of the process is required. Several websites provide details and tutorials on the AHP. The following example mirrors one such tutorial.⁹⁸ In our survey, we asked participants to compare the MOEs to each other in pairs, assigning rank according to their preference of one MOE over the other. The scale depicted in Figure 10 shows how the assignment of preference works. For our example, we are comparing responsiveness and endurance. A weighting assignment on the scale to the left of one indicates the survey participant prefers responsiveness to endurance. Numbers to the right

⁹⁷ Thomas L. Saaty, "Decision Making, Scaling, And Number Crunching," *Decision Sciences* 20.2 (1989): 405.

⁹⁸ Analytic Hierarchy Process AHP Tutorial, August 26, 2008
<<http://people.revoledu.com/kardi/tutorial/ahp/AHP.htm>>.

indicate a preference of the endurance attribute. If both attributes are considered to be of equal importance, the respondent indicates this preference by assigning a one to the comparison.



Figure 10. MOE Preference Scale

The survey asked respondents to continue this paired comparison for all attributes, which in our study equates to the five MOEs. The responses to the pairwise comparison are used to populate a reciprocal matrix, where responses are entered into the top half of the matrix, and the reciprocal values are entered into the bottom half to create a comparison matrix (Figure 11). From the reciprocal matrix the AHP computes the five corresponding Eigen vectors, which we computed using *MATLAB* for our example (Figure 12). The principal Eigen vector corresponds to the highest Eigen value (Figure 13).

| | Responsiveness | Access | Coverage | Endurance | Flexibility |
|----------------|----------------|---------------|---------------|---------------|---------------|
| Responsiveness | 1 | $\frac{1}{5}$ | 4 | 3 | 5 |
| Access | 5 | 1 | 2 | 3 | 1 |
| Coverage | $\frac{1}{4}$ | $\frac{1}{2}$ | 1 | $\frac{1}{3}$ | 4 |
| Endurance | $\frac{1}{3}$ | $\frac{1}{3}$ | 3 | 1 | $\frac{1}{2}$ |
| Flexibility | $\frac{1}{5}$ | 1 | $\frac{1}{4}$ | 2 | 1 |

Figure 11. Reciprocal Matrix of Pairwise Comparisons

$$W = \begin{bmatrix} 0.5399 & -0.1199 + 0.3337i & -0.1199 - 0.3337i & -0.0163 + 0.3694i & -0.0163 - 0.3694i \\ 0.7276 & 0.7396 & 0.7396 & 0.6978 & 0.6978 \\ 0.2661 & -0.3801 - 0.0306i & -0.3801 + 0.0306i & 0.2514 - 0.2103i & 0.2514 + 0.2103i \\ 0.2274 & 0.0853 + 0.2778i & 0.0853 - 0.2778i & -0.4561 - 0.1756i & -0.4561 + 0.1756i \\ 0.2378 & 0.0643 - 0.3053i & 0.0643 + 0.3053i & -0.0630 + 0.1618i & -0.0630 - 0.1618i \end{bmatrix}$$

Figure 12. Corresponding Eigen Vectors from Reciprocal Matrix

$$W = \begin{bmatrix} 0.5399 \\ 0.7276 \\ 0.2661 \\ 0.2274 \\ 0.2378 \end{bmatrix}$$

Figure 13. Principle Eigen Vector from Reciprocal Matrix

The sum of the column of the principle Eigen vector in our example is 1.9988. Using this number to normalize the values in the matrix, we get the values that correspond to preference in the pairwise comparison (Figure 14).

$$\bar{W} = \begin{bmatrix} 0.270 \\ 0.364 \\ 0.133 \\ 0.114 \\ 0.119 \end{bmatrix}$$

Figure 14. Normalized Principle Eigen Vector

What the matrix above example tells us is that the survey respondent, in the pairwise comparison of all the MOEs, most preferred the access attribute (36.4%), followed by responsiveness (27%), coverage (13.3%), endurance (11.4%), and flexibility (11.9%).

4. The Analytical Hierarchy Process and Consistency

One construct that distinguishes the AHP from other decision processes is the allowance for inconsistency in the comparisons.⁹⁹ In mathematics, the property of transitivity simply states that if $A > B$, and $B > C$, then $A > C$. Furthermore, if A is 5 times greater than B, and B is 3 times greater than C, then A must be 15 times greater than C. In the AHP, the transitive property is still relevant when applied to choices. However, due to human nature when making comparisons, respondents often give inconsistent answers with regard to the

⁹⁹ Analytic Hierarchy Process AHP Tutorial.

second principle of transitivity, which is the degree of preference. Thus, Saaty has allowed within the AHP a level of acceptable inconsistency based upon the number of choices available to the decision maker. When making a pairwise comparison, a decision maker must still be consistent as to which alternative is preferred. However, he now has an allowable level of inconsistency in relation to the degree of preference expressed, so that "... [the process] is not inhibited by the need for transitive relationships and instead of ignoring such relationships, provides a measure of inconsistency so that the decision maker can proceed accordingly."¹⁰⁰ This is especially important when comparing attributes or alternatives where no quantitative data is available.

To determine consistency, the AHP computes the Eigen value of the reciprocal matrix of pairwise comparisons. From our example reciprocal matrix above, we computed the corresponding Eigen values using MATLAB (Figure 15). Important to the process of establishing a consistency rating is the identification of the principle Eigen value. The principle Eigen value is the largest Eigen value from the matrix (Figure 16).

$$\lambda = \begin{pmatrix} 6.7060 & 0 & 0 & 0 & 0 \\ 0 & -0.4056 + 2.8875i & 0 & 0 & 0 \\ 0 & 0 & -0.4056 - 2.8875i & 0 & 0 \\ 0 & 0 & 0 & -0.4474 + 1.5206i & 0 \\ 0 & 0 & 0 & 0 & -0.4474 - 1.5206i \end{pmatrix}$$

Figure 15. Corresponding Eigen Value from the Reciprocal Matrix

$$\lambda_{\max} = 6.7060$$

Figure 16. Principle Eigen Value

¹⁰⁰ Ernest H. Forman and Saul I. Gass, "The Analytic Hierarchy Process: An Exposition," *Operations research* 49.4 (2001): 48.

To evaluate consistency, the AHP uses the ratio of the Consistency Index (CI) to the Random Consistency index (RI).¹⁰¹ Perfect consistency within the comparison survey is achieved when the principle Eigen value is equal to the number of objects compared. For our pairwise comparison survey, we asked respondents to compare the five attributes for preference (n=5). The Consistency Index measures the degree of difference between these two numbers (Figure 17). The Random Consistency Index (RI) is a table derived by Saaty that gives inconsistency allowances based on the number of choices available, so that a minimum of 10% allowance is included in every matrix size (Figure 18).

$$CI = \frac{\lambda_{\max} - n}{n - 1} = \frac{6.7060 - 5}{5 - 1} = 0.4265$$

Figure 17. Consistency Index

| n | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|----|---|---|------|-----|------|------|------|------|------|------|
| RI | 0 | 0 | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

Figure 18. Random Consistency Index¹⁰²

To compute the overall Consistency Ratio for the survey, the ratio shown in Figure 19 is calculated. When CR < 10%, the survey results are considered within the acceptable standards for the AHP. For our example, the results show the Consistency Ratio outside the accepted range. In this case, the survey results may be excluded from the study or a new survey with clearer instructions may be necessary.

$$CR = \frac{CI}{RI} = \frac{0.4265}{1.12} = .38 \text{ or } 38\% \text{ (unacceptable inconsistency)}$$

Figure 19. Consistency Ratio Calculation

¹⁰¹ Saaty, 85-89.

¹⁰² Analytic Hierarchy Process AHP Tutorial.

5. Applying the Analytical Hierarchy Process to Attain MOE Weights

The study used *Expert Choice 2000*® decision support software, designed to implement the AHP, to derive a dominance matrix from the participant responses and then use this matrix to assign relative values to each of the MOEs as described earlier. After receiving all the surveys, the raw scores were input into an Excel spreadsheet. A linear transformation formula, Equation 1, was applied to the raw scores to convert them to the scale used by the *Expert Choice 2000* software and then the average score was found. The survey database is in Appendix F.

$$\text{New Score} = \frac{\text{nub} - \text{nlb}}{\text{oub} - \text{olb}} (\text{original score} - \text{olb}) + \text{nlb}$$

nub=new upper bound

nlb=new lower bound

oub=old upper bound

olb=old lower bound

Equation 1: Linear Transform Formula¹⁰³

Figure 20 shows the pairwise comparison matrix populated with the average survey results for scenario A. From the matrix, our study utilized the AHP to develop the relative weights for each MOE for scenario A, utilizing the mathematical concepts described earlier, and depicted in Figure 21. For scenario A, we can see that survey respondents regarded access as the most important trait for an ISR or communications platform to have. Figure 22 shows the average survey response input for scenario B. Survey respondents indicate a preference for endurance for this scenario, as depicted in Figure 23. The survey matrix for scenario C is Figure 24. Coverage was the most dominant attribute preferred for this scenario, as shown in Figure 25.

¹⁰³ Analytic Hierarchy Process AHP Tutorial 3.

As seen in the bottom left corner of each figure, the Consistency Ratio is 0.02 for each scenario. Since the inconsistency tolerance utilized by the AHP is 10% or less, the overall consistency ratio for our survey is mathematically consistent within the AHP defined limits.

| Compare the relative importance with respect to: Scenario A | | | | | |
|---|-------------|--------|----------|-----------|-------------|
| | Responsiv | Access | Coverage | Endurance | Flexibility |
| Responsiveness | | 1.86 | 1.0 | 1.52 | 1.0 |
| Access | | | 2.0 | 1.96 | 2.57 |
| Coverage | | | | 1.0 | 1.67 |
| Endurance | | | | | 2.95 |
| Flexibility | Incon: 0.02 | | | | |

Figure 20. MOE Survey Results for Scenario A

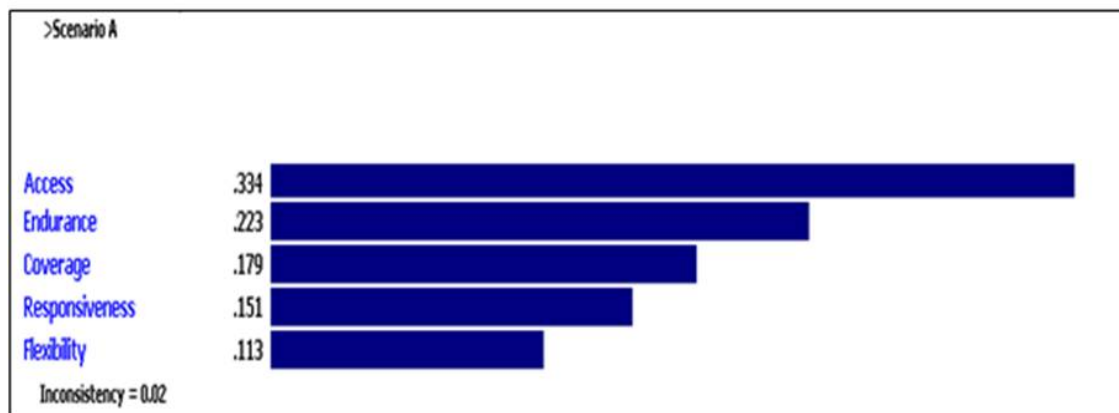


Figure 21. Scenario A MOE Weights Based On Survey Results

| Compare the relative importance with respect to: Scenario B | | | | | |
|---|-------------|--------|----------|-----------|-------------|
| | Responsiv | Access | Coverage | Endurance | Flexibility |
| Responsiveness | | 1.0 | 1.0 | 2.43 | 1.0 |
| Access | | | 1.43 | 1.81 | 1.0 |
| Coverage | | | | 1.0 | 1.76 |
| Endurance | | | | | 3.62 |
| Flexibility | Incon: 0.02 | | | | |

Figure 22. MOE Survey Results for Scenario B

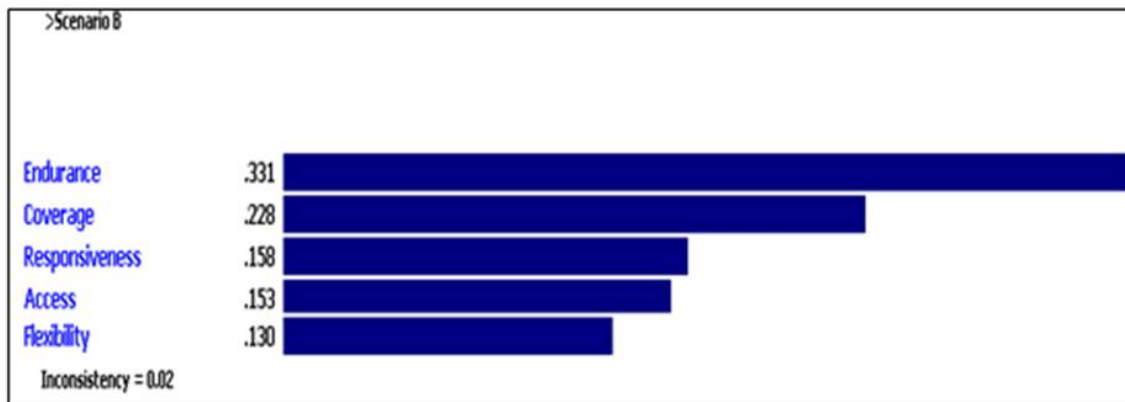


Figure 23. Scenario B MOE Weights Based on Survey Results

Compare the relative importance with respect to: Scenario C

| | Responsiv | Access | Coverage | Endurance | Flexibility |
|----------------|-------------|--------|----------|-----------|-------------|
| Responsiveness | | 2.05 | 1.0 | 1.0 | 1.0 |
| Access | | | 2.57 | 1.67 | 1.0 |
| Coverage | | | | 1.0 | 1.0 |
| Endurance | | | | | 1.24 |
| Flexibility | Incon: 0.02 | | | | |

Figure 24. MOE Survey Results for Scenario C

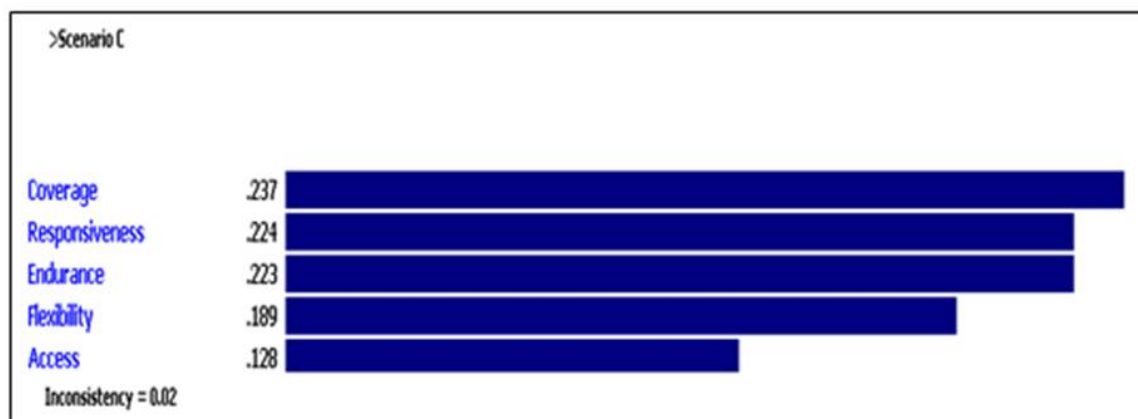


Figure 25. Scenario C MOE Weights Based on Survey Results

G. PLATFORM CAPABILITY ASSESSMENT

After completing the MOE evaluation and processing the results using the AHP to formulate a score for each MOE within each scenario, we began the process of evaluating the individual platforms within each scenario for comparison. To begin the process, tables were created depicting the pros and cons for each platform under each MOE, as shown in Appendix A. The information in the tables is not rank ordered in any way. The subsequent step entailed a pairwise comparison of the individual platforms within each scenario.

1. Assumptions

In order to conduct the comparison we made several assumptions that would allow us to effectively draw out the individual strengths and weaknesses of each platform within the given scenario. These assumptions include the following sections.

a. ORS is a Functional Program

We assumed the Operationally Responsive Space program is functioning within its designed concept. In order to compare the ability of the platforms to replace lost assets, which was covered by our definition of responsiveness, we had to assume that lost TacSat assets could be replaced within the design concept of this program.

b. Pre-positioned Forces

Similar to any military operation in a foreign theater, we assumed assets would be pre-positioned in or near theater to support deployed forces. This allowed us more realistically evaluate responsiveness.

c. *No Assets are Held in Reserve*

We assumed that all available assets would be utilized to support forces within each scenario. This may seem intuitive, however, risk aversion may prompt some to believe that we would not employ some assets until certain conditions had been met on the battlefield. An example would be high intensity combat without air superiority. Although not ideal, history has proven that this worst-case scenario is a possibility that the DoD must be prepared to conduct, and that in this environment every available asset would be used to support the warfighter on the ground, regardless of the value of the asset.

d. *Platforms Must Move*

We assumed the acquisition of new targets in new geographical areas would require the platform to move from its current location. Since our analysis was designed to assess the capability of the individual platforms and not the sensors they carry, the assessment of responsiveness would require the platform to relocate and not just move its sensors to cover new areas of interest.

e. *Platform Dynamics and Limitations Apply to Each Scenario*

An assessment of the endurance of the individual platforms must take into consideration how the asset would be employed, to include such things as range limitations, level of authority for the assets use, etc. This too may seem intuitive, however, in comparing simple platform metrics, this can lead to erroneous results. For example, the flight time duration of many medium altitude UAS appear to give the asset a broad range of coverage, if the asset were on a straight line, one-way trip. However, the normal operating range for the asset and its typical employment is well within these limits.

f. Only the Scenario at Hand is Evaluated

For the sake of consistency, no consideration is given to the normal culminating points or tempo of combat operations. Normal combat operational tempo results in periods of high and low intensity combat as units reach the limits of their logistical reach or require time to regroup and, therefore, transition between periods of offensive and defensive operations. For our comparison of each platform within the given scenarios, only the scenario at hand was considered, without regard to the transition that may occur to the other scenarios.

g. Only Single Platform Comparisons

For comparison, only singular platforms were considered. The entire "system" or overlapping use of platforms to provide continued target acquisition would not effectively differentiate the capabilities of the alternatives, and, therefore, was not considered.

Using these assumptions, we compared each of the platforms together in a qualitative assessment within each scenario. From this assessment, we developed pairwise comparison scores to enter into the *Expert Choice 2000* program and derive an AHP result. The platform databases reflect the changes in the qualitative assessment of each platform within each scenario.

Along with the qualitative assessment of the alternatives, we also attempted to quantify the attributes of the platforms for metric comparison. Although the AHP results are not derived from this quantification, comparison of the results with our qualitative assessment assisted in validating our results. The entire table of platform metrics used to quantify the capability of each of the alternatives for comparison is in Appendix C. Since the intangible benefits these systems provide often escape quantification, our initial concern in evaluating the platforms was that the alternatives might be extremely difficult to compare and that finding comparable measures with attainable data for quantitative analysis would be difficult to achieve.

In the following sections, we will try to capture both aspects of the platform analysis. The first part of each section discusses the platform capabilities and the qualitative assessment conducted for comparison. The second part of each section discusses the quantitative analysis we conducted for comparison to our qualitative assessment results. Finally, at the end of the qualitative and quantitative comparisons, we provide the AHP results for each of the platforms within the given scenarios. For the sake of consistency throughout the analysis, all references to alternatives follow the numbering system listed in Table 2.

| Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 |
|---|--------------------------|---|---|
| TacSat (LEO for ISR) (HEO for Comm) | High Altitude Airship | High Altitude Unmanned Aerial Vehicle | Medium Altitude Unmanned Aerial Vehicle |

Table 2. Alternative Numbers

2. Platform Responsiveness Qualitative Assessment

Responsiveness was earlier defined as the ability to react to new missions in a different geographical area and begin passing the user actionable data. Additionally, it is the ability to replace an asset if lost. The following assumptions were made. First, the platform is already airborne when directed to execute a new mission. Second, if an asset is lost, the replacement platform is not airborne, but ready to respond when replacement is necessary. Each platform was evaluated against this definition, with the stated assumptions, and the conclusions are explained below.

a. *Tactical Satellites*

Tactical Satellites have a number of advantages and disadvantages in Responsiveness. First, TacSats do not necessarily need a forward-based or in-theater footprint to be responsive to new tasking. (Theater commanders may eventually request the capability for direct theater downlink for a long duration

mission, but it is not necessary at mission inception.) In the event of responding to a new mission in a different geographical area, the TacSat may not require any adjustments for expeditious response. Physics dictates the orbital mechanics and, in many cases, a TacSat already in orbit might be the fastest platform to respond. Additionally, a single TacSat might be able to respond to multiple new missions nearly simultaneously due to its global access (orbit dependant). Some of the TacSat drawbacks include possible delays in response if the satellite just made a pass over the target area once a new mission is identified. Additionally, if a satellite is in a low-inclination orbit, and a mission is identified in a high latitude location, then a satellite might not be able to respond at all if it is not carrying enough fuel to make the inclination change. If a TacSat is lost and a replacement is necessary, the infrastructure to do so in a timely manner today does not exist. Future progress in ORS is necessary for satellite responsiveness to become a reality.

b. High Altitude Airships

High Altitude Airships, like TacSats, have the advantage of not needing a forward-deployed footprint to conduct missions or replace a lost asset. This enables quicker response to new missions in distant locations or locations with limited support infrastructure. Additionally, HAAs have the ability to change payloads based on mission requirements. However, HAAs do have a slow cruising speed (about 30 knots) which must be taken into consideration. For new missions in the same geographic area this might not be an issue because of its large coverage area, but if a lengthy transit is required, the HAA may need days to respond. Additionally, payload swap-out may require a trip back to the hangar, which will not be in-theater. Lastly, the HAA may be limited based on its decreased access to high latitudes during winter months.

c. *High Altitude UAS*

High Altitude UAS, the Global Hawk for thesis purposes, would most likely be the first airborne asset available for a new mission in a distant geographic area because of its long range and high speed. This long range allows it to operate at great distances from its base, but forward bases, not necessarily in theater, are required. Like the HAA, the Global Hawk can change payloads for specialized missions. Since visits to base are more frequent with the Global Hawk, payload exchange can be done more easily than with the HAA.

d. *Medium Altitude UAS*

Medium Altitude UAS, like the Army Sky-Warrior, due to the level of control (the division level) may be the most responsive to the tactical warfighter. The Sky-Warrior can quickly respond to new missions within their current geographic area. However, they do require a significant amount of forward deployed support and therefore are unable to quickly respond to a new mission outside of their current theater.

e. *Considerations*

In assessing the responsiveness of each platform, we considered each vehicle's ability to travel to the newly designated target (driven by platform speed or advertised response timeline for ORS). Consider, for example, the slow speed of the airship to move to new targets and to move replacement assets into place for lost platforms in contrast with the speed of the other platforms. With a functioning ORS program, TacSat assets could be launched on short notice to provide operational support within hours. Assuming that the HAA would have to reposition to respond to a newly identified target outside of its footprint, the TacSat may be the more responsive asset (dependent on the distance the airship would have to travel to acquire the target and the amount of time until the TacSat orbit would encompass the target within its footprint).

For asset replacement, this would also be the case. Using the capability of the ORS program, lost assets could be replaced within hours, whereas to replace a lost HAA asset, even from forward deployed bases, would likely take longer.

With forward deployed assets, and with the speed of the platform, the High-Altitude UAV would most likely be able to respond to new targets more quickly than the TacSat, even with an ORS capability. Likewise, to replace a lost asset, whether from CONUS or from bases overseas, the High-Altitude UAV would likely provide a more responsive capability than the TacSat.

When considering the Medium-Altitude UAV, we also considered the level of authority at which it is retained and tasked. Additionally, since it is a division level asset, and not a strategic asset like the other alternatives, it would likely be closer to the forces in need of its use. Likewise, the command chain to request its employment or launch a replacement asset would be shorter, which ultimately equates to more responsiveness. The nature of the other platforms, as strategic assets, would more than likely take longer to respond to the warfighter's request for new target coverage.

3. Platform Responsiveness Quantitative Assessment

For the quantitative analysis of platform responsiveness, we attempted to capture the ability of each platform to respond to a new target in a new geographic location, measured in hours (Table 3). To measure the ability of each alternative to respond, we calculated the amount of time each platform required to move the following distances:

| | Western Iraq to Northern Afghanistan | Western Iraq to Eastern Iraq | Southern Iraq to Northern Iraq |
|-----------------|---|---|---|
| Distance | 2977 km | 683 km | 885 km |

Table 3. Distance Table¹⁰⁴

For the sake of our evaluation, we chose the middle distance (885 kilometers) as the required distance of travel to the new area of interest, as the task to travel across theater is the most likely scenario for our alternatives. Ultimately, any distance that would require the platform to move to a new location could be used for comparison. We then used the platform characteristics to determine the length of time required for the alternative to reach the new geographic area. The results are shown in Table 4. For alternatives 2-4, we assumed the area of interest to be along a linear path from the platform's current location. However, we did not take into consideration any operating range limitations of the individual platforms, but instead operated under the assumption that users employing the platforms would do this. To achieve the results, we divided the distance traveled by the speed of each platform (56, 630, and 218 kilometers per hour, respectively).^{105 106 107}

¹⁰⁴ Google Earth, August 27, 2008 <<http://earth.google.com/>>.

¹⁰⁵ Jamison, Porche, and Sommer, 16.

¹⁰⁶ Global Hawk - US AIR FORCE / Fact Sheet 1oct2005, October 1, 2005, August 19, 2008 2008 <<http://www.mindfully.org/Technology/2005/Global-Hawk-USAF1oct05.htm>>.

¹⁰⁷ Steven Short, Sky Warrior (MQ-1C) Air Vehicle Specifications, 2008), August 21, 2008 <<https://www.us.army.mil/suite/doc/12178059>>.

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 |
|--|---|---------------|---------------|---------------|
| Responsiveness (Target 885 km distant) | <u>LEO:</u> 1.5 hours (best) 22 hours (worst) Average: 11.75 hours <u>HEO:</u> 0 hours (best) 24 hours (worst) Average: 12 hours | 15.8 hours | 1.4 hours | 4.1 hours |

Table 4. Quantitative Responsiveness Assessment

Since the TacSat is subject to the physical constraints of orbital mechanics, a straight-line distance measurement does not neatly apply for the sake of comparison. Instead, we used the average of the best and worst-case travel times for the platform with regard to orbital parameters and average response time to a new area of interest along the earth's equator. For the LEO ISR platform, the best-case scenario is when the new geographic area of interest is within the footprint of the next orbiting pass of the satellite. With an altitude of 410 kilometers in a circular orbit, the next orbital pass over the area of interest would be within its orbital period of 1.5 hours. The worst-case scenario for the LEO platform is when it has just passed over the area of interest and will not revisit the location until the earth completes its revolution, or approximately 22 hours later. Table 5 shows how we obtained the orbital period and revisit time for the LEO platform. Since a newly identified area of interest may fall within either of these cases, we used the average of the two to establish a responsiveness measurement of 11.75 hours.

| Period (min) | Space Between Orbit Tracks (deg at Equator) | Degrees to km Conversion | Number of Revs to Cover Circumference of Earth | Time to Cover Circumference of Earth (hours) |
|---|--|----------------------------|---|---|
| $P = 2\pi(a^3 / \mu)^{1/2}$ | $S = \frac{P}{1436 \text{ min}} \rightarrow 360 \text{ deg}$ | $\text{deg} \cdot 111.319$ | $\text{Revs} = \frac{\text{Circumference}}{\text{kms / rev}}$ | $\text{Time} = \text{Period} \cdot \text{Revs}$ |
| 92.77 | 23.26 | 2588.84 | 15.48 | 22 |
| Constants: | | | | |
| C (circumference of earth--km) | | | 40,075.16 | |
| Re (radius of earth--km) | | | 6378.14 | |
| a (semi-major axis--km) | | | 6788.14 | |
| μ (earth gravitational constant --km ³ s ⁻²) | | | 398600.50 | |

Table 5. Determination of Period and Revisit Time for LEO Platform¹⁰⁸

Likewise, the HEO platform response time is best analyzed in light of the orbital constraints on the vehicle. The best-case scenario is when the area of interest is within the coverage area of the platform. With a dwell time at apoapsis of 1-2 hours per orbit and six orbital revolutions per day, the HEO platform (with its large footprint area) provides some persistence that the LEO platform does not offer.¹⁰⁹ The worst-case scenario for the HEO platform is when it completes its dwell time and begins its approach toward periapsis. During this time in its orbit, as the earth spins beneath its orbit, the platform will have a coverage gap of 24 hours before it returns to the target area. An average time to attain a target in a new geographic area is, therefore, the average of these two cases, or 12 hours. Table 6 shows how we obtained the orbital period and revisit time for the HEO platform.

¹⁰⁸ Wiley J. Larson and James Richard Wertz, *Space Mission Analysis and Design*, 3rd ed. (El Segundo, Calif; Dordrecht; Boston: Microcosm; Kluwer, 1999) 137, 172.

¹⁰⁹ Doyne, et al.

| Period (min) | Space Between Orbit Tracks (deg at Equator) | Degrees to km Conversion | Number of Revs to Cover Circumference of Earth | Time to Cover Circumference of Earth (hours) |
|---|--|----------------------------|---|---|
| $P = 2\pi(a^3 / \mu)^{1/2}$ | $S = \frac{P}{1436 \text{ min}} \cdot 360 \text{ deg}$ | $\text{deg} \cdot 111.319$ | $\text{Revs} = \frac{\text{Circumference}}{\text{kms / rev}}$ | $\text{Time} = \text{Period} \cdot \text{Revs}$ |
| 239.00 | 59.92 | 6669.87 | 6.01 | 24 |
| Constants: | | | | |
| C (circumference of earth--km) | | | | 40,075.16 |
| Re (radius of earth--km) | | | | 6378.14 |
| a (semi-major axis--km) | | | | 6788.14 |
| μ (earth gravitational constant --km ³ s ⁻²) | | | | 398600.50 |

Table 6. Determination of Period and Revisit Time for HEO Platform₁₁₀

4. Platform Responsiveness AHP Results

The following show the platform qualitative analysis results of responsiveness in the various given scenarios using *Expert Choice 2000* and applying the AHP (Figures 26-28). The results show that the medium altitude UAS was assessed as providing the most responsiveness in all three scenarios. These results are similar to the quantitative results, although they differ in the assessment of the two UAS platforms. This is because the quantitative analysis only considers the platform speed when assessing responsiveness, whereas the qualitative analysis also considers the level of authority at which control over the various platforms is maintained and relative proximity to the target.

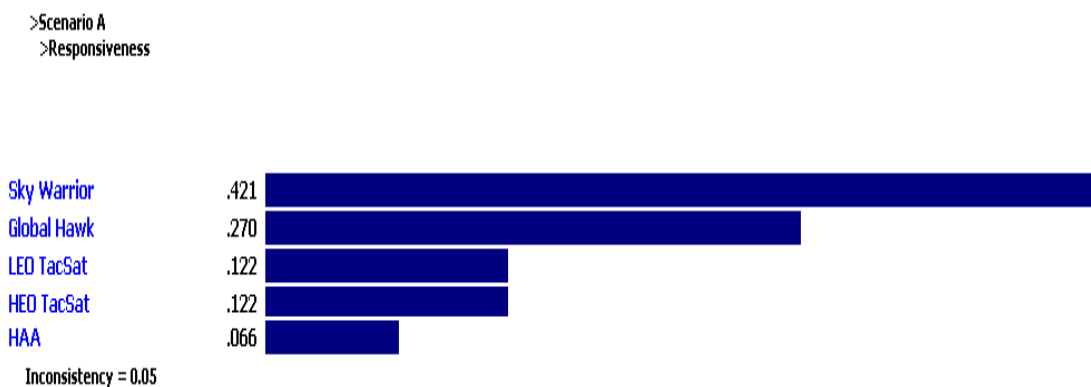


Figure 26. Platform AHP Results for Responsiveness in Scenario A

>Scenario B
>Responsiveness



Inconsistency = 0.02

Figure 27. Platform AHP Results for Responsiveness in Scenario B

>Scenario C
>Responsiveness



Inconsistency = 0.04

Figure 28. Platform AHP Results for Responsiveness in Scenario C

5. Platform Access Qualitative Assessment

Access was defined earlier as the geographic extent of what the payload can see over time – i.e. no time limit; for example, a single satellite in polar orbit has a global access area. This is critically important when you have a great need to see into an uncooperative state in peacetime or into an area where you lack air superiority during wartime. Ideally, you would have low altitude global access at all times.

a. Tactical Satellites

TacSats with an inclination of approximately 90° have global access. Satellites with an inclination of less than 90° can provide access to the latitude equal to and below their inclination (some access may be achieved at slightly higher latitude depending upon satellite altitude and sensor field of view).

Sovereign airspace does not exist at orbital altitudes and therefore satellites do not need over-flight permissions from hostile nations. This gives the satellite the unimpeded ability to collect intelligence on a global scale.

b. High Altitude Airships

High Altitude Airships are capable of accessing most areas over the earth. Airships are not limited by fuel requirements due to their solar panels and hydrogen fuel cells. Therefore, they effectively have an unlimited range. As briefly stated earlier, polar access (above 60° latitude) is limited to summer months due to the amount of sunlight needed to power the airship via its photovoltaic solar panels. Additionally, some latitudes might experience some seasonal variations in the winds at high altitudes that might not be favorable to airship operations. Yet, because of their altitude, airships are not greatly affected by most weather. As with UAS and other aircraft, HAA's will need over-flight authorization to enter the sovereign airspace of other nations during peacetime or air superiority during wartime. These platforms do have some access to denied areas and their ability to peer into areas where air superiority has not been established. However, they are at risk when doing so.

c. High Altitude UAS

High Altitude UAS such as the Global Hawk also have a number of limitations on their access. First, the Global Hawk engines are powered by fuel and therefore have a limited range (2400 nm radius with the ability to provide 24 hours time-on-station).¹¹¹ Global Hawk has the ability to cruise at high altitudes, above most of the weather problems, but, as with most aircraft, dealing with inclement weather at lower altitudes can be problematic. Additionally, as with other aircraft Global Hawks will need over-flight authorization to enter the sovereign airspace of other nations during peacetime or air superiority during

¹¹¹ Global Hawk - US AIR FORCE / Fact Sheet 1oct2005.

wartime. However, because of their altitude, they can peer somewhat into denied areas from safe sanctuaries, or fly into denied areas at risk.

d. *Medium Altitude UAS*

Medium Altitude UAS such as the Sky-Warrior have the greatest limitation on their access. They are limited by all the elements that limit the Global Hawk but to a greater extent in range and weather limitations.

e. *Considerations*

One of the key strengths of any satellite is its ability to see into denied territory. When assessing the platform access capability before air superiority is established, we assumed the other assets would still be used but that their access would be limited.

The most likely employment technique for airborne platforms before air superiority is established would be to constrain their use to the immediately airspace from the rear area of operations up to the forward line of troops (FLOT). Even though total air superiority is not yet established, military forces will attempt to establish control of the airspace above ground forces in order to support the warfighter on the ground. Constraining the airborne assets to this area, however, would limit their ability to gain access to the denied territory beyond the FLOT, which would be a function of their individual sensor capability, the altitude at which they operate, and the limitations established for their employment (i.e., how close they were allowed to get to the denied territory).

Regardless, if the situation called for it and access was essential for warfighter support, the platform most likely to be employed inside denied territory would probably be the medium altitude UAV. This target is the least expensive of the alternatives, has enough range to gain access to a large portion of denied territory once launched, provides the smallest target footprint for the enemy, and can be flown at various altitudes to make surface-to-air missile targeting much more difficult.

Once air superiority is attained, all the platforms would have equal access to the area of interest. The relative superiority of the satellite in this attribute would then be greatly reduced.

6. Platform Access Quantitative Assessment

For our quantitative analysis of access, we attempted to capture the ability of each platform to provide access to denied territory. The TacSat alternative has no limitations on access if it is in an orbit of the appropriate inclination for the area of interest. The percentage of the earth's surface it can see is a matter of the orbital constraints applied at launch. The decisions of the platform users are the driving factor in deciding such orbital parameters as altitude, orbit type, and inclination based on mission analysis and type of coverage desired. To assess the access capability of Alternatives 2-4 we used the scenario of how much access into North Korea the alternatives would be able to gain if employed from South Korea or international waters, given as a percentage of the total land mass of the country, or 120,540 km².¹¹² As shown in Figure 29, the circular footprint of each platform is a function of altitude and the viewing angle capability of the sensor. To assess the access area of each platform, we first had to find the radius of each alternative's footprint by applying the trigonometric function shown below.

¹¹² List of Countries by Land Mass [Ranked by Area], September 10, 2008
<http://www.mongabay.com/igapo/world_statistics_by_area.htm>.

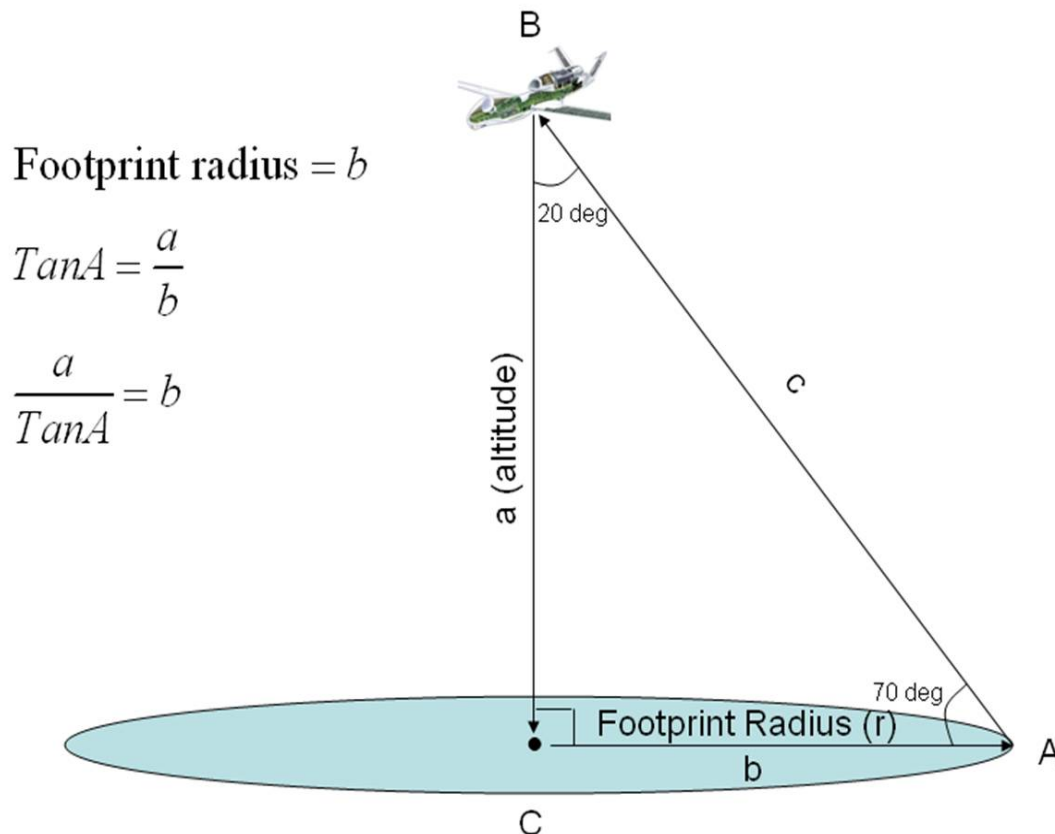


Figure 29. Sensor Footprint Radius Diagram

To determine the percentage of denied territory each alternative is capable of accessing, we made several assumptions. First, we assumed each platform is only able to access from outside the denied territory's boundaries. By definition, "denied" implies this standard, however, access *could* be gained if, under duress, loss of the platform is a risk that the warfighter is willing to bear. Secondly, for the sake of geometric simplicity, the land mass given for North Korea was used to calculate the area of a circle for platform access comparison. Finally, for consistency, we used a 20 degree off nadir pointing angle for all three platforms, which is a common capability found on commercial imaging satellites.¹¹³ If considering communications access, platforms could potentially look almost to the horizon depending of the frequency in use. However, if

¹¹³ WorldView-1 Satellite Sensor Specifications and Information | Satellite Imaging Corp, August 27, 2008 <<http://www.satimagingcorp.com/satellite-sensors/worldview-1.html>>.

imagery is normally the primary concern, and given no ‘stand-off’ distance for the platform, Figure 30 depicts how the amount of access of each platform into denied territory is a factor of half of its footprint area. The radius of the denied territory minus the radius of the platform sensor allows us to calculate how much of the denied territory is out of the reach of each alternative. Appendix E contains the table depicting the calculations to determine access area. Table 7 below depicts the results of those calculations.

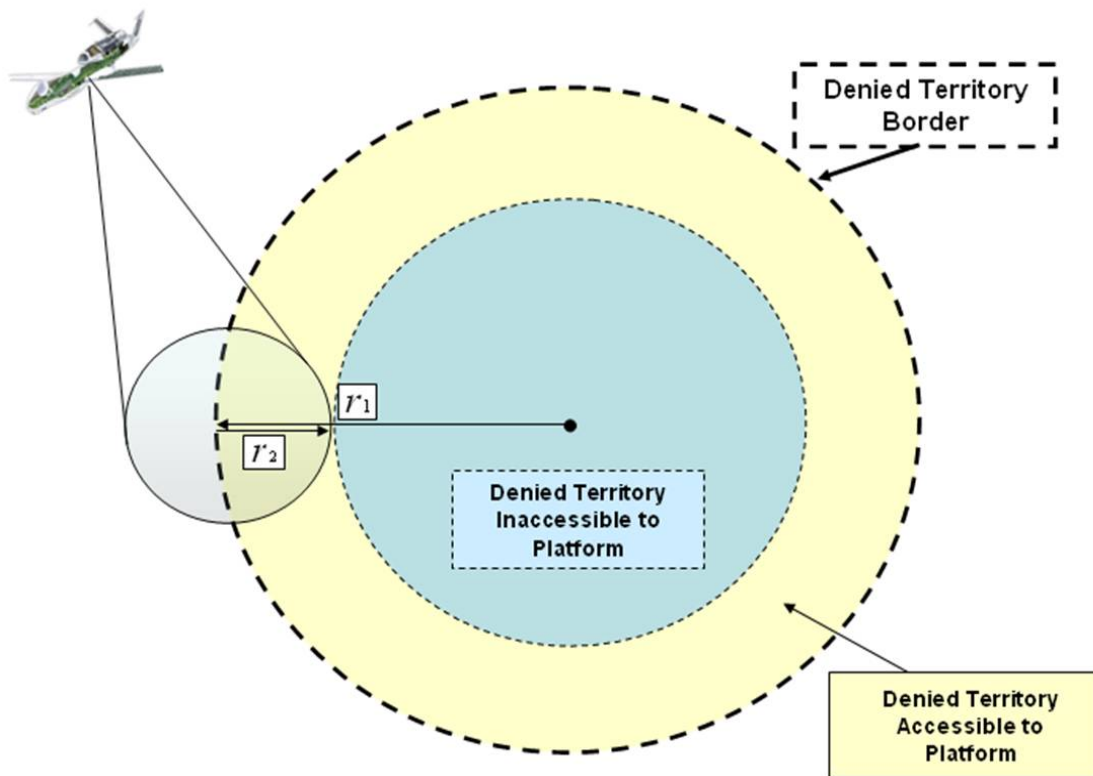


Figure 30. Access Measurement

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 |
|---|---------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Access (% of Denied Territory Scenario) | 120,540 km ² = 100 % | 8,793 km ² = 7.3 % | 8,793 km ² = 7.3 % | 3,380 km ² = 2.8 % |

Table 7. Quantitative Access Assessment

7. Platform Access AHP Results

The results of the qualitative assessment mirror the results of the quantitative analysis (Figures 31 and 32). The satellite platforms obviously have no access limitations in scenario A, unlike the other platforms. In addition, the range limitations and altitude of employment, which affect access in scenario A, are also reflected in the results. By contrast, once air superiority is attained (scenarios B and C), all the alternatives would have equal access to denied territory, as indicated by the AHP scores.



Figure 31. Platform AHP Results for Access in Scenario A



Figure 32. Platform AHP Results for Access in Scenario B & C

8. Platform Coverage Qualitative Assessment

Coverage is defined above as an indication of how quickly the system can view the access area measured in hours. This dictates how well you can conduct your mission within your access area.

a. Tactical Satellites

TacSats, because of their high altitude have the greatest access, but not the greatest coverage. Coverage rates will vary depending on the type of orbit. Orbits are generally optimized for the spacecraft mission. Imaging satellites are normally placed in low earth orbit (LEO) to maximize their imaging resolution. The disadvantage of LEO orbit is that satellites at lower altitudes have the greatest velocity (as opposed to satellites in higher orbits) and therefore spend only short amounts of time over the target area – normally only five to ten minutes. The result is a small and fast moving coverage area. It is important to understand that access does not automatically equate to more imaging on the part of ISR platforms. It is simply the potential area within which the platform can image. An example would be the IKONOS earth imaging satellite. At 680 kilometers altitude, the IKONOS has a very large access area; however, the images that IKONOS provides are typically 121 km² -- much smaller than the actual access area.¹¹⁴ By contrast, communications satellites are generally placed in higher orbits to increase the size of their footprint and to maximize their dwell time over a certain geographic area. The representative communications satellite, TacSat-4, uses a highly elliptical orbit (HEO) to accomplish this. This type of orbit results in a larger and slower moving coverage footprint.

b. High Altitude Airships

High Altitude Airships, due to their altitude, have a large footprint. The footprint of a single airship covers almost all of Afghanistan. However, because the airship remains relatively stationary, it has all the time necessary too fully image everything in its footprint. Airships, if payload volume and mass allows, may be able to place multiple cameras aboard to complete multiple taskings at once.

¹¹⁴ Spot Image - Ikonos, September 5, 2008 <<http://www.spotimage.fr/web/en/183-ikonos.php>>.

c. *High Altitude UAS*

High Altitude UAS normally operate at the same relative altitude as the high altitude airships. This allows them similar sensor coverage area. However, because of their greater forward air speed, high altitude UAS can move quicker to provide coverage outside of their immediate footprint if necessary. An additional benefit that a high altitude UAS is that it can lower its altitude to capture high priority EO/IR images below cloud cover when required.

d. *Medium Altitude UAS*

Medium Altitude UAS operate at a much lower altitude (25,000 ft vs. 65,000 ft) than their high altitude counterparts do. This results in a smaller sensor footprint. However, medium-altitude UAS attempt to compensate with their high forward airspeed to cover areas that an airship and high-altitude UAS can provide coverage for based on their altitude.

e. *Considerations*

Although the TacSat can access more area than the other platforms in scenario A, the amount of ISR coverage the LEO platform can achieve within its access area is limited because of its limited persistence in its orbital flight.

Assuming the same sensor package is used aboard both the airship and high altitude UAS platform, the mission duration limitations of the HA UAV would hamper its ability provide a continuous flow of coverage data. However, since both platforms operate at the same altitude the HA UAV gains a slight edge because of its maneuverability. The equal mission duration times of the high and medium altitude UAS allow both platforms to provide coverage of a larger area, but the higher altitude of the HA UAS gives the platform the opportunity to provide more coverage.

9. Platform Coverage Quantitative Assessment

The study calculated order of magnitude coverage for each platform and listed the results in hours (Table 8). Coverage calculations included the amount of time necessary for a platform to image an area of 120,540 km² (the area of North Korea).¹¹⁵ Satellite Toolkit simulations were run using the Quickbird satellite orbital information because it closely mirrors the orbit of TacSat-2. The simulation revealed that it would take 24 days for the satellite to image the entire land mass. However, vendor statistics for the Global Hawk Integrated Sensor Suite state that the Global Hawk can image 40,000 nm² (137,192 km²) in 24 hours.¹¹⁶ Assuming the sensor capabilities of the HAA are equal to or better than those of the Global Hawk, then each platform can image the land mass in less than one day. The Sky Warrior footprint is roughly 1/3 of the footprint of the Global Hawk and HAA. Therefore, we estimate that it will take three times as long to image the same land area. The Footprint width calculations utilized several equations from Wertz and Larson.¹¹⁷ Appendix D gives a complete listing of footprint width calculations for each platform.

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 |
|---|--------------------------|---------------|---------------|---------------|
| Coverage (hours to provide ISR coverage of designated area) | LEO: 24 days = 576 hours | 24 hours | 24 hours | 72 hours |

Table 8. Quantitative Coverage Assessment

10. Platform Coverage AHP Results

The results of the qualitative assessment are shown in Figures 33-35. The AHP results show that even though the LEO satellite platform may have

¹¹⁵ List of Countries by Land Mass [Ranked by Area].

¹¹⁶ Raytheon, 2.

¹¹⁷ Larson and Wertz, 166.

advantages in access for scenario A, its limited time over the target area would greatly decrease its ability to provide coverage of the area of interest. These results are similar to those we found in the quantitative analysis. Although the quantitative results show that the airship and high altitude UAV provide equal coverage of the designated land mass, the mobility of the UAV gives it a considerable edge in coverage in the qualitative analysis.

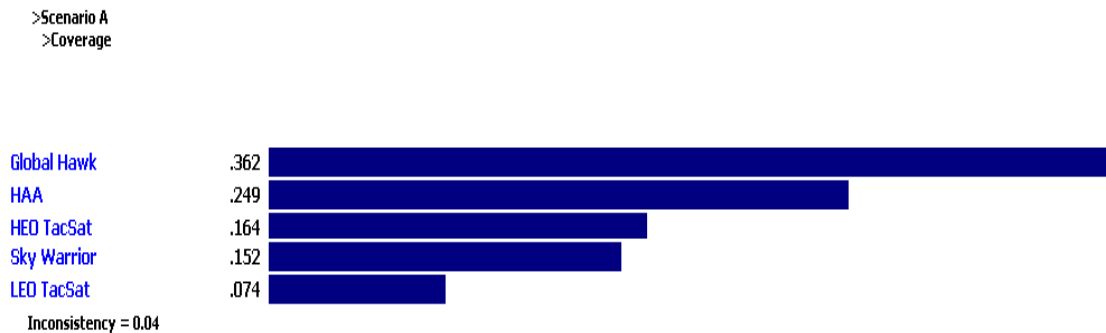


Figure 33. Platform AHP Results for Coverage in Scenario A

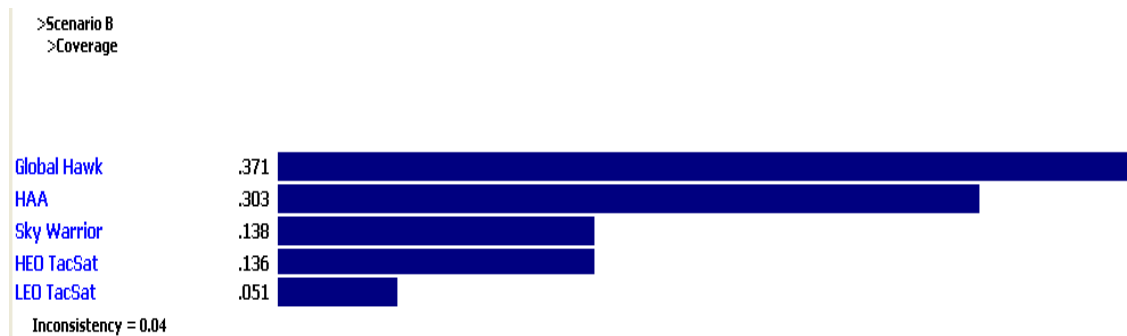


Figure 34. Platform AHP Results for Coverage in Scenario B



Figure 35. Platform AHP Results for Coverage in Scenario C

11. Platform Endurance Qualitative Assessment

a. Tactical Satellites

TacSats, as for coverage, vary in this MOE depending on the type of orbit in which they are placed. Satellites in LEO (the normal orbit for imaging satellites) have only a small fraction of the endurance of other platforms. Higher orbits result in greater endurance. However, even in the HEO proposed by TacSat-4, endurance is not the TacSat's strong suit (only one to two hours of dwell per pass with approximately three passes per day).¹¹⁸ Therefore, to achieve a high level of endurance with a TacSat, a constellation of satellites would be required so that as one is passing over the horizon, another one is already in place and delivering the required services.

b. High Altitude Airships

High Altitude Airships have the greatest endurance of the proposed platforms. The objective HAA will attempt to achieve a year of on-station time. This results in a high degree of confidence that the platform will be there and ready when needed.

c. High Altitude UAS

High Altitude UAS (the Global Hawk) can remain aloft for approximately 38 hours at a time. However, UAS require a great amount of maintenance and fuel to consistently achieve this level of endurance. As described later, they can maintain an average availability rate of just over 30%. Therefore, as with TacSats, multiple platforms will be needed to maintain the desired level of endurance for persistent ISR and communications if more than 38 hours of support is needed.

¹¹⁸ Doyne, et al, 4.

d. Medium Altitude UAS

Medium Altitude UAS almost mirror the high altitude UAS in their endurance. The Sky Warrior has approximately 36 hours of endurance as opposed to the Global Hawks' 38 hours of endurance.¹¹⁹

e. Considerations

The real strength of the airship is in its individual platform endurance and payload capacity. The HAA has the ability to spend more time providing data of its coverage area. This may be of somewhat diminished significance in scenario A, due to the TacSat's ability to access more area. If the warfighter wants ISR data of a target that the HAA cannot access then he really does not care how long the platform can stay aloft. However, as the scenario changes, the endurance quality may become a more important trait to the warfighter, e.g., fleeting targets in low-intensity operations. It is also important to note that the endurance attribute is not as significant when the airship is compared to the HEO communications satellite, with its longer dwell time over the target area.

Although the endurance of HAA is much better than both the UAV platforms, the importance of that trait within scenario A may be much lower than in scenario B or C. Within scenario A, although the airship dominates in its ability to provide endurance, if the HAA cannot access the target where coverage is needed, the platform's endurance is meaningless. The warfighter would gladly give up some of that capability to gain in the other attributes such as access.

12. Platform Endurance Quantitative Assessment

The study measured each alternative's endurance in hours, as shown in Table 9. For the sake of comparison, in the calculation for endurance

¹¹⁹ Sky-Warrior ERMP UAV System.

for each alternative we made the stipulation that the measurement would span the length of six months to ensure we understood the alternative's comparative ability.

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 |
|---|--|--|---|---|
| Endurance (# hours over 6 month period) | LEO: $\approx 10 \text{ min/day} \times 182 \text{ days}$ $= 30.33 \text{ hours}$ HEO: $7 \text{ hours/day} \times 182 \text{ days}$ $= 1274 \text{ hours}$ | $24 \text{ hrs} \times 182 \text{ days}$ $= 4368 \text{ hours}$ | $4368 \text{ hours} \times .315 \text{ Average \% Utility}$ $= 1376 \text{ hours}$ | $4368 \text{ hours} \times .315 \text{ Average \% Utility}$ $= 1376 \text{ hours}$ |

Table 9. Quantitative Endurance Assessment

For the LEO platform in Alternative 1, we obtained the maximum time in view for a single target on the ground at zero degrees elevation from Space Mission Analysis and Design.¹²⁰ Mission briefings for the Alternative 1 HEO platform provided the maximum time in view for this vehicle.¹²¹ The typical mission duration for Alternative 2 is six months, so this platform is capable of providing continuous coverage over the established time. To calculate endurance for Alternative 3 and Alternative 4 we used a calculation for utility from a previous study.¹²² The function defines the proportion of time spent on station by the UAV in performing its mission, and is calculated using Equations 2 and 3. The study showed that the mission utility of Alternative 3 ranged from 0.21-0.42. For our endurance calculation, we used the average of this range, or a mission utility of 0.315. We multiplied this percentage against the total possible hours in six months to determine endurance for the platform. Since Alternative 4 possesses a proportionate mission duration capability to Alternative 3, we applied the same mission utility measurement to calculate endurance for Alternative 4 as well.

¹²⁰ Larson and Wertz, Back cover, column 9.

¹²¹ Doyne, et al.

¹²² "Competitive Sourcing", "OMB Memorandum M-07-01, Report to Congress on FY 2006 (2005) 28/07/2008 <http://management.energy.gov/cs_report_fy2006.pdf>.

$$\text{UAV Utility} = \frac{\text{Time on Station}}{\text{Mission Cycle Time}}$$

Equation 2: UAV Utility Measurement

$$\text{Mission Cycle Time} = \text{Time on Station} + \text{Transit Time} + \text{Maintenance Time}$$

Equation 3: UAV Mission Cycle Time

13. Platform Endurance AHP Results

The results of the qualitative assessments are shown in Figures 36-38. The AHP results show that, as in the quantitative assessment, HAA platform dominates in the endurance attribute. Likewise, the LEO ISR platform's assessment in the endurance attribute continuously ranks as the weakest platform.

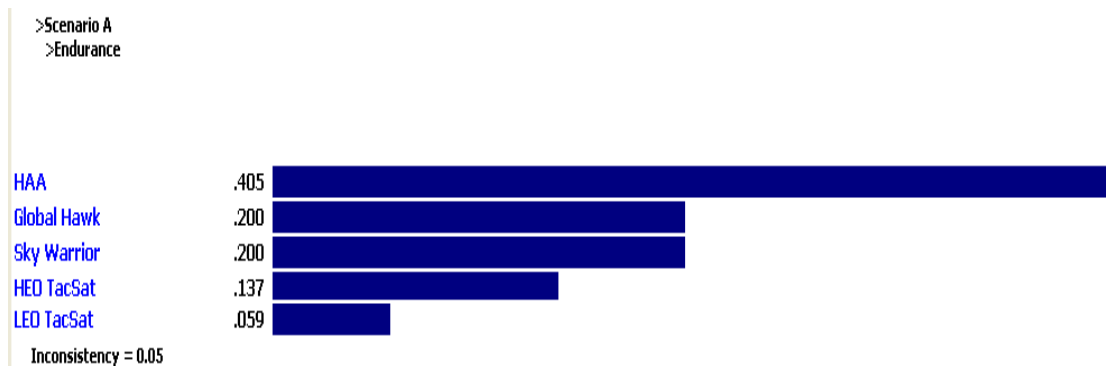


Figure 36. Platform AHP Results for Endurance in Scenario A

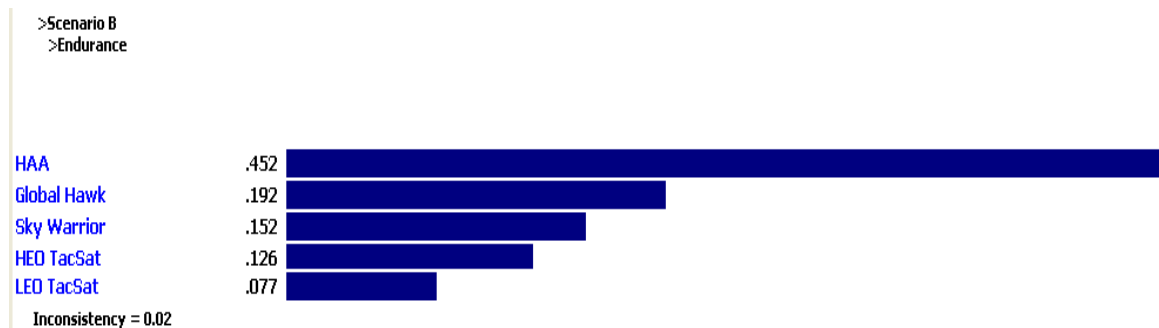


Figure 37. Platform AHP Results for Endurance in Scenario B



Figure 38. Platform AHP Results for Endurance in Scenario C

14. Platform Flexibility Qualitative Assessment

a. *Tactical Satellites*

TacSats, once placed in orbit, cannot be altered and therefore, offer limited flexibility. Additionally, as described earlier, it is very difficult to perform an imaging mission and a communications mission simultaneously on the same platform because of the orbits needed to accomplish the different missions.

b. *High Altitude Airships*

High Altitude Airships, because of their ability to carry a large payload, are able to accomplish both the ISR and communications missions simultaneously on the same platform. Additionally, payloads can be changed when the airship returns to its dock. This payload exchange capability allows for sensor upgrades and mission-dependent sensor specialization.

c. *High Altitude UAS*

High Altitude UAS can accomplish the ISR mission to a very high level. However, its payload capacity is packed with ISR equipment leaving little room for communications payloads. Payloads can be changed out as needed, but because of its reputation as an ISR platform, its inability to remain on station for long periods of time, and its current CONOPS, commanders would be loathe to use the Global Hawk as their primary means of long-range communications.

d. *Medium Altitude UAS*

Medium Altitude UAS mirrors the high altitude UAS in most ways. However, the Army is planning multiple variants for the Sky Warrior. One variant will provide some WIN-T communications relay capabilities once WIN-T is fielded.¹²³ This variant will not carry missiles or SAR to save the power and weight necessary for the communications payload.

e. *Considerations*

As the fight transitions to sustained low-intensity operations this attribute may become more important to the warfighter. Usually at the onset of combat operations, where scenario A is the more likely possibility, all available assets are brought to bear against the enemy in a combined arms operation. Typically, the warfighter is inundated with assets at his disposal and may be hard pressed to effectively employ all of them. However, as troop rotations and equipment breakage becomes more apparent over the sustainment of operations, this abundance often turns to a scarcity of assets where units often are in competition for their use. Accordingly, flexibility becomes a more highly sought after attribute in scenario C than in the previous scenarios.

15. Platform Flexibility Quantitative Assessment

Based upon the previously discussed definition, the study based the flexibility measurement for each alternative on the ability to perform both ISR and communications from a single platform. The measurement for flexibility was a qualitative assessment of each alternative, with each platform scored according to the scale depicted in Table 10.

¹²³ Short.

| Alternative Score | Flexibility Measure |
|-------------------|--|
| 1 | Fully capable. Performs both missions from single platform |
| 2 | Moderately capable. Performs both missions with payload exchange. |
| 3 | Limited capability. Performs both missions. Requires multiple platforms. |

Table 10. Flexibility Assessment Scale

Table 11 depicts the assignment of scores based on the assessment scale. Alternative 1 received the lowest score because of its limited capability to conduct both ISR and communications missions from the same platform. Typically, ISR satellites fly at LEO for increased resolution. This orbital constraint, however, limits the footprint width of the platform and gives it very limited duration of coverage, which makes it less than ideal as a communications platform. Conversely, communications satellites typically fly at HEO for longer dwell times over areas of interest to provide uninterrupted communications coverage. HEO orbits, however, are not favorable to electro-optical imaging. Characteristically, the configuration design for these platforms accomplishes only one or the other of the two missions in our study. Alternatives 3-4 both have the ability to change configurations to accomplish one of the two mission areas. Therefore, the assessment of moderately capable applied. The assessment of full mission capability for Alternative 2 is based on the ability to carry multiple payloads for both communications and ISR. The scores shown in Table 11 were converted the AHP scale using Equation 1 shown earlier.

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 |
|--|---------------|---------------|---------------|---------------|
| Flexibility (Qualitative Assessment) | 3 | 1 | 2 | 2 |

Table 11. Qualitative Flexibility Assessment

16. Platform Flexibility AHP Results

The results of the qualitative assessment are shown in Figures 39-41. The AHP results show that the HAA's ability to conduct both ISR and communications missions simultaneously provides a great advantage for the platform over the other alternatives in scenario A. The capability to arm the UAS platforms with different sensors for the specified mission allows them to score higher in utility than the satellite platforms.



Figure 39. Platform AHP Results for Flexibility in Scenario A



Figure 40. Platform AHP Results for Flexibility in Scenario B



Figure 41. Platform AHP Results for Flexibility in Scenario C

H. COMBINING RELATIVE WEIGHTS WITH PLATFORM ANALYSIS

With relative weights developed for each MOE from our survey of experts, and with a comparison score for each alternative based on the qualitative analysis, the next step is to combine the relative weights with the platform scores using the utility function in Equation 4 for each scenario.

$$\text{Utility} = f \left[X_1(R) + X_2(A) + X_3(C) + X_4(E) + X_5(F) \right] \times 100$$

Equation 4: Alternative Utility Scoring Equation

The function contains variables for Responsiveness, Access, Coverage, Endurance, and Flexibility (R, A, C, E, and F respectively), and treats cost as an independent variable. The variable MOE weights (X_1 through X_5) for each scenario are derived from the survey results. The platform MOE variables (R, A, C, E, and F) are derived from the analysis of platform metrics in each MOE category.

Once the databases for the weights of the MOEs within each scenario and the weights for the platforms are populated, *Expert Choice 2000* can then calculate the overall scores for each platform within each scenario. Figures 42 through 44 depict the platform scores for Scenarios A through C respectively, with all three scenarios weighted equally. Each figure depicts, *ceteris paribus*,

which alternative provides the most efficient ISR and communications platform in each scenario as a function of the platform qualitative scores and the relative weighted preference of each attribute by the survey respondents.

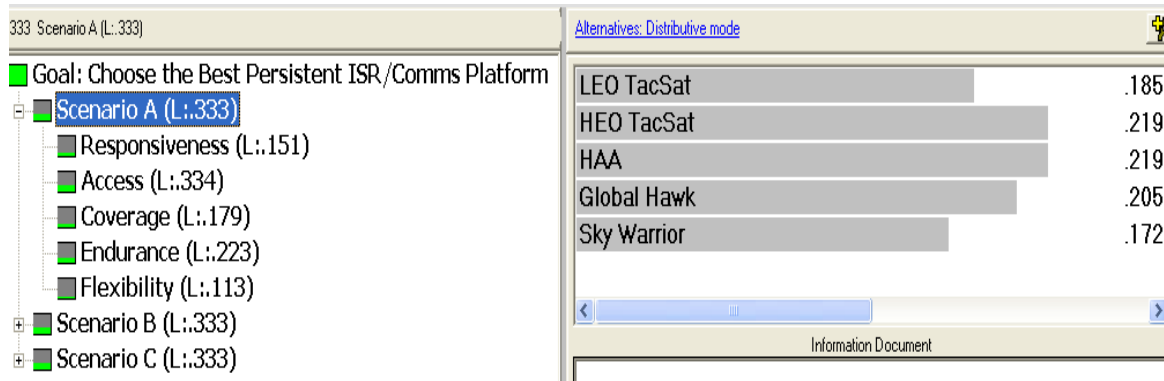


Figure 42. Final Platform Scores for Scenario A

As Figure 42 depicts, the HEO TacSat platform and the HAA are rated equally high in scenario A using the AHP. This is probably due to the high access rating of the HEO platform and the relative weight of access as an alternative attribute in this scenario. Without air superiority, access to denied territory is limited with the other platforms. However, satellite access of denied territory is not dependent on air superiority, which is a distinct advantage of the TacSat platform in scenario A. Although the HAA score within the scenario may lead the decision maker to believe the preference for both platforms is equal, it is important to understand how the AHP achieved these results. The endurance attribute is rated second highest in importance in scenario A. The HAA dominates in this attribute. Therefore, although the HAA access score is lower, the platform's much higher endurance score gives it an overall rating within the scenario that is the equivalent of the HEO TacSat. It is important to realize, within this scenario without air superiority, this overall result may only hold true when the area the warfighter wants coverage of is within the HAA's access area

while operating in secure airspace. Without air superiority, if the warfighter needs access to denied territory beyond the range of the HAA, only the satellite platforms can accomplish the mission.

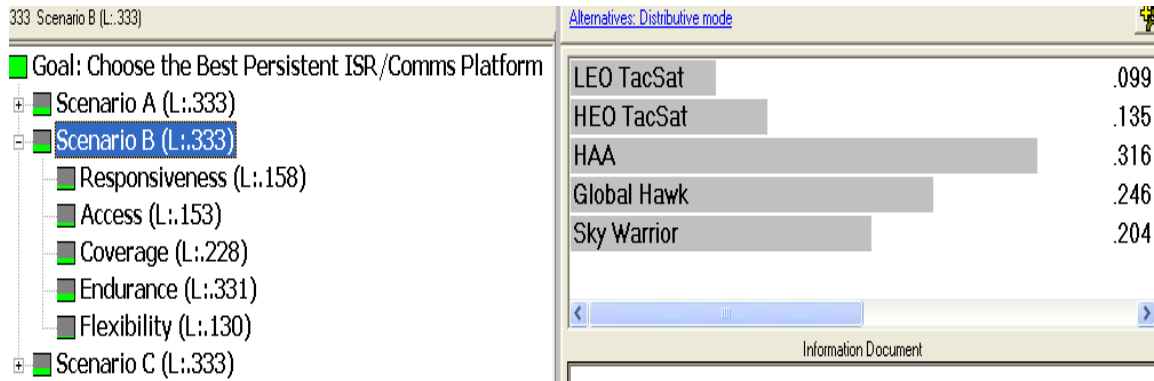


Figure 43. Final Platform Scores for Scenario B

As Figure 43 depicts, the HAA platform is rated highest in scenario B using the AHP. The apparent advantage appears to be largely due to the platform's superior performance in endurance over the other alternatives. Once air superiority is established, the advantages of having a platform that is able to provide persistent coverage is a unique advantage of the HAA over the other ISR and communications vehicles. The HAA also scored high in coverage, the second highest MOE.

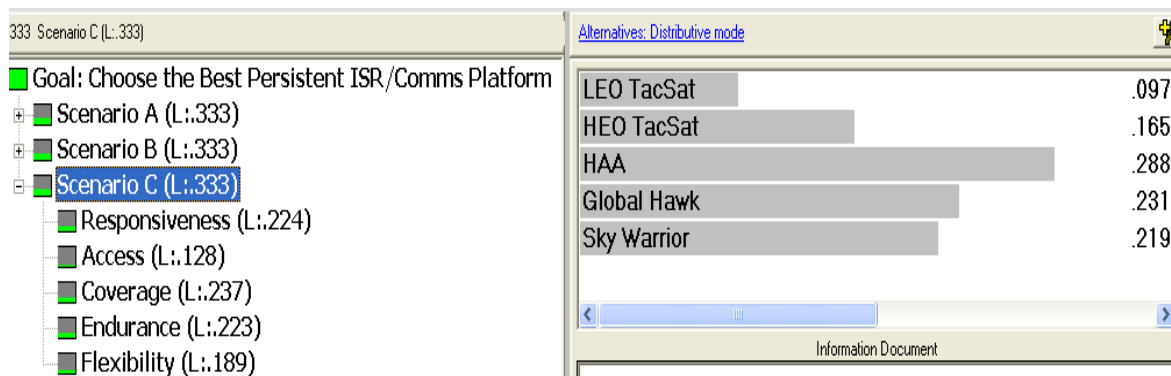


Figure 44. Final Platform Scores for Scenario C

As stated earlier, the GWOT is the primary focus of the DoD and remains the most likely mission for the military for the near and mid-term threat analysis.¹²⁴ Scenario C is not dissimilar to ongoing operations in Iraq and Afghanistan. Our AHP analysis of ISR and communications platforms shows that, within scenario C, the HAA is the preferred alternative (Figure 44). This is not intended to take away from the capabilities of the other systems, like the UAS with its strong responsiveness attribute. Although our survey did not result in respondents identifying responsiveness as the most important attribute in scenario C, fleeting, high-payoff targets in this environment may require platforms that can adjust quickly to changing missions and conduct short turnaround times between tasks. The relative weights of the MOEs for scenario C show that our pool of experts considered almost all the attributes (with the exception of access) to be of near equal value within the definition of the scenario.

Although scenario C best represents the current operational focus of the DoD, it is not representative of the most dangerous course of action for which the military must prepare. In its role to project combat power in support of strategic objectives, the United States Army and Marine Corps must prepare for the full spectrum of warfare, which the recent eruption of hostilities between Russia and Georgia reasserts. To analyze the impact of the likelihood of each scenario on the alternative scores, we weighted each scenario differently and recorded the results. This technique allowed us to analyze the impact on alternative scores by increasing the most likely scenario (scenario C) and the most dangerous (scenario A). The overall best choice may change based upon how each scenario is weighted. For comparison, the following four figures show the platform scores when all scenarios are evenly weighted and when each scenario carries 60% of the weight while the other two scenarios each carry 20% of the weight (Figures 45-48).

¹²⁴ Marine Corps Vision and Strategy 2025.

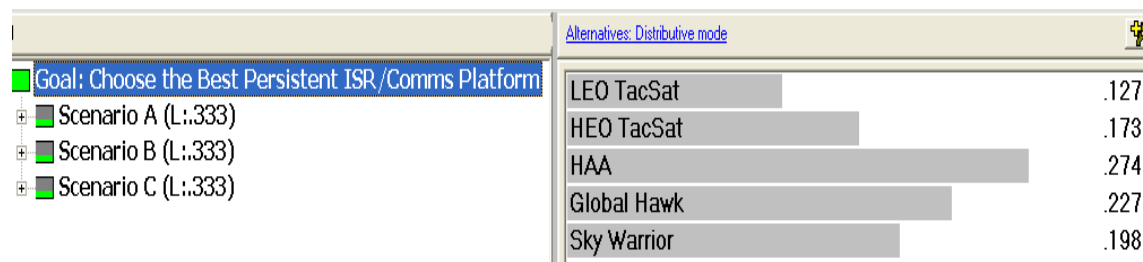


Figure 45. Platform Scores With All Scenarios Weighted Evenly

Figure 45 depicts the AHP results when all scenarios are weighted evenly. If the DoD devotes resources to preparation for all three scenarios evenly distributed, and it invested in the alternative platforms based on this presumption, the AHP shows that the HAA investment would yield the most benefit to the user based on the relative weights of the MOEs used in this study and the platform qualitative assessment. Notably, the two platforms most preferred in this scenario are the HAA and high altitude UAS, while the LEO TacSat is considered the worst choice.



Figure 46. Overall Platform Scores with Scenario A Weighted Highest

If scenario A is considered to be the most dangerous course of action for which the DoD must be prepared, and then weighted the investment in alternatives based on that presumption, then the HAA investment yields the most benefit to the user (Figure 46). The TacSat ability to access denied territory despite a lack of air superiority gives it a decided advantage in scenario A, but the DoD investment would still have to consider the other scenario possibilities and allocate budget amounts (40%) based on the possibility of scenario B or C. Using this logic, the HAA yields the highest AHP results. With the higher rating

of the access attribute in scenario A, the HEO TacSat, with its higher access score, is rated almost equally with the high altitude UAS. The LEO platform, however, is again scored lowest.



Figure 47. Overall Platform Scores with Scenario B Weighted Highest

Figure 47 depicts the alternative results when the likelihood of Scenario B is higher than the other alternatives. As the figure shows, if DoD investment in alternatives is weighted according to these results, the HAA investment would again be highest, followed by the other platforms. Of note, the LEO satellite platform once again scores lowest in effectiveness in scenario B.

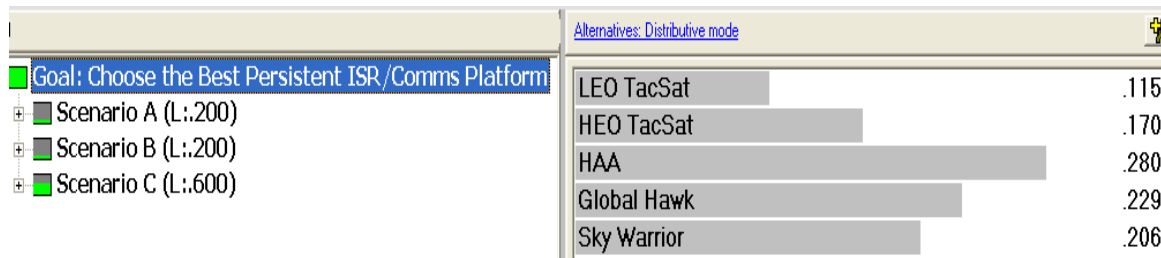


Figure 48. Platform Scores with Scenario C Weighted Highest

Figure 48 depicts the alternative results when the likelihood of Scenario C occurring is higher than the other alternatives. As the figure shows, if DoD investment in platforms is weighted according to the AHP results of this possibility, then the HAA investment would be highest, followed by the other platforms. The LEO TacSat achieves the lowest effectiveness score when scenario C is weighted highest, making it the lowest rated platform across the board for both equal weighting of the scenarios and when each scenario is given preferential weight based on expected future events.

I. CHAPTER SUMMARY

This chapter begins by exploring the reasons for, and the importance of, the analysis. The study explored different methods of analysis, such as a cost benefit analysis, before deciding that a cost effectiveness analysis with an economics approach to be the correct prototype to follow. We described the analysis process and began by exploring different MOEs to fit the study. Sound MOEs were chosen and each platform was assessed against those MOEs. The analysis methodology included a description of the Analytical Hierarchy Process and how the study used that process for analysis. Next, the study used a survey of academics and military personnel to determine user preference among the MOEs, and then used the AHP to assign weights to each MOE in three different scenarios. We conducted a qualitative assessment of all the platforms in a pairwise comparison within each scenario to develop platform AHP scores, which we attempted to compare to a quantitative analysis of platform metrics for veracity.

The study combined the MOE weights and platform qualitative performance scores to determine the best platform for each scenario. The best overall platform could then be determined by weighting all scenarios evenly or by favoring one scenario over the others. In the following chapter, we will dig deeper to study the real effects of budget constraints on investment. In particular, we will analyze fixed budget effects on the platforms, and then explore the maximum effectiveness one could achieve based on a variety of alternative methods of investment in the platforms analyzed. Finally, we will also attempt to show the optimal mix of alternatives for investment in ISR and communications platforms.

IV. CONCLUSIONS

Since September 11, 2001, the need [for bandwidth] has increased eight-fold in Central Command due to the war in Afghanistan and the pursuit of terrorists in the region.¹²⁵

A. DETERMINING COST ALTERNATIVES

Since cost is used as an independent variable for this study, there is no impact due to cost in the AHP analysis process detailed thus far. However, to conduct a cost-effectiveness analysis, the next step is the inclusion of the cost variable to determine the impact on overall effectiveness. Each of the platforms analyzed have merit in meeting warfighter demands, and consequently will continue to be procured by the DoD. However, the right mix of platforms should be considered in an overarching strategy. The following are examples of various investment alternatives considered. The total program cost as of September 2007 of the Global Hawk UAS (\$9.6 billion) will be the baseline cost ceiling.¹²⁶ The program cost includes money already spent and GAO estimates of the money it will take to complete the program through the final procurement of all systems. The following alternatives will be utilized in the comparison for cost-effectiveness:

1. All TacSats

One alternative is to invest the entire amount of funding into LEO and HEO tactical satellites. It is understandable that this is not a practical investment strategy, because it would eliminate the inherent capabilities of the other platforms. However, it is a useful technique for gauging the total amount of capability the TacSats provide, when compared to the other platforms, if given

¹²⁵ David Hughes, "Pentagon Targets Bandwidth Expansion," *Aviation Week and Space Technology* (2003): 57.

¹²⁶ United States. Government Accountability Office., 91.

the entire investment amount. By using the Air Force Research Laboratory cost estimate for an average tactical satellite of \$87 million (not including launch cost), the DoD could purchase 110 LEO TacSats or 110 HEO TacSats.¹²⁷ Once the ORS program advances to the point where TacSat launches become routine, the price per satellite will drop closer to the Congressional goal of \$40 million per small satellite.¹²⁸ However, once launch costs and satellite control operations are factored in, the actual number of satellites purchased would be lower. However, Iridium can provide global communications coverage for years with a LEO constellation of only 66 small satellites.¹²⁹ If a TacSat could be made that could adequately provide both responsive communications and responsive ISR capabilities this alternative might be acceptable. Figure 49 shows the overall effectiveness score for the first alternative using Equation 4 (see Appendix G for effectiveness score calculations). The calculated effectiveness score is based on the average platform effectiveness multiplied by the investment purchase of 110 TacSats.

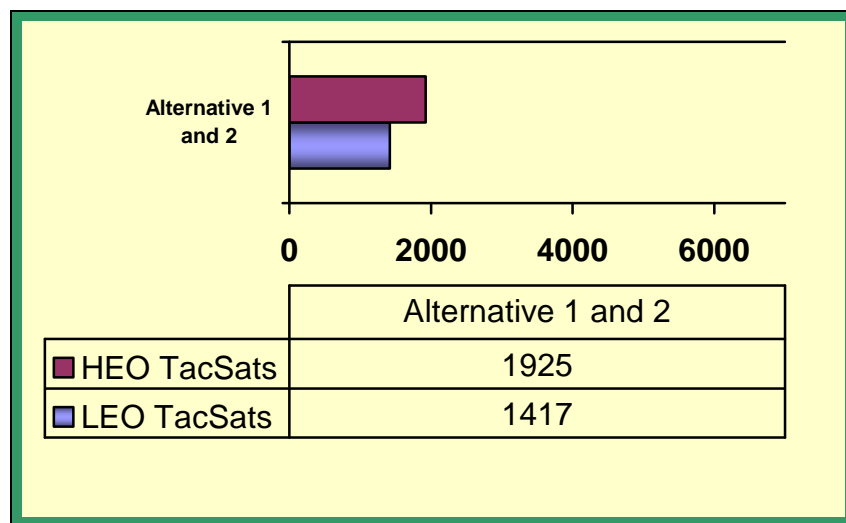


Figure 49. Alternative 1 and 2 Effectiveness Score

¹²⁷ Government Accountability Office, 11.

¹²⁸ Ibid.

¹²⁹ Iridium, August 29, 2008 <<http://www.iridium.com/about/about.php>>.

2. All HAAs

The second alternative is to invest the entire amount of funding into a high-altitude long-endurance airship such as the HAA. By using the RAND cost estimate for a HAA of \$50 million each, the DoD could purchase 192 HAAs for the expenditure cost of the Global Hawk UAS.¹³⁰ Operations, maintenance, prototype costs, and hangar infrastructure will likely significantly reduce the actual number purchased. However, if only 50 are purchased, one could be dedicated to every active duty Army division headquarters and their four brigade combat team (BCT) headquarters. This would significantly enhance communications and ISR capabilities for the warfighter commanders. Figure 50 shows the overall effectiveness score for the second alternative (see Appendix G for effectiveness score calculations). The calculated effectiveness score is based on the average platform effectiveness multiplied by the investment purchase of 192 HAAs.

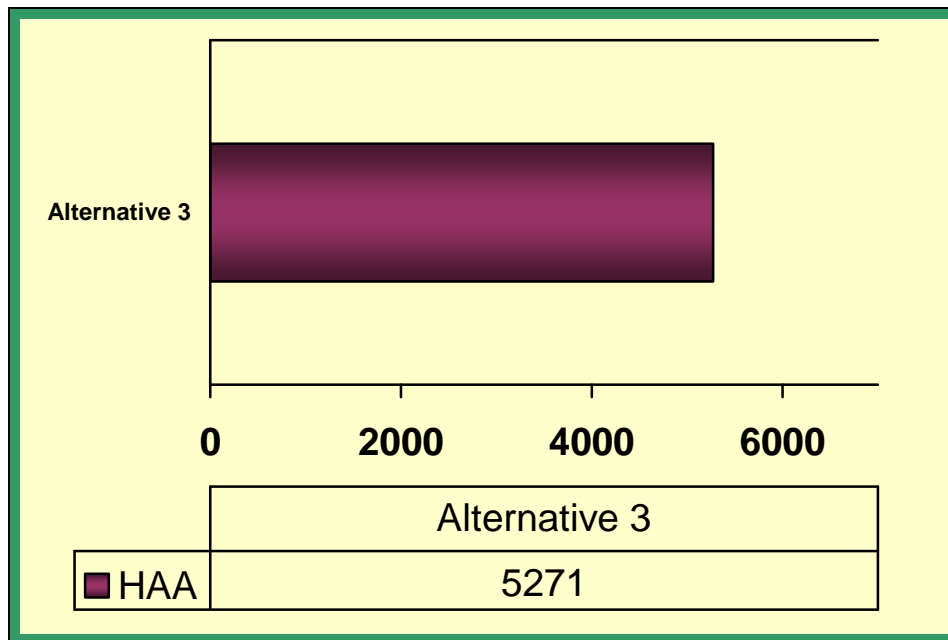


Figure 50. Alternative 3 Effectiveness Score

¹³⁰ Jamison, Porche, and Sommer, 8.

3. All High-Altitude UAS

Another alternative is to invest the entire amount of funding into high-altitude UAS such as the Global Hawk. According to the Government Accountability Office, the Global Hawk program is investing \$9.6 billion for 54 UAS.¹³¹ Using the example above, this would be enough Global Hawks for every active Army division and BCT headquarters. However, as an Air Force asset and costing nearly \$178 million apiece, it is unlikely that these platforms would be dedicated to the tactical fight. Figure 51 shows the overall effectiveness score for the third alternative (see Appendix G for effectiveness score calculations). The calculated effectiveness score is based on the average platform effectiveness multiplied by the investment purchase of 54 UAS.

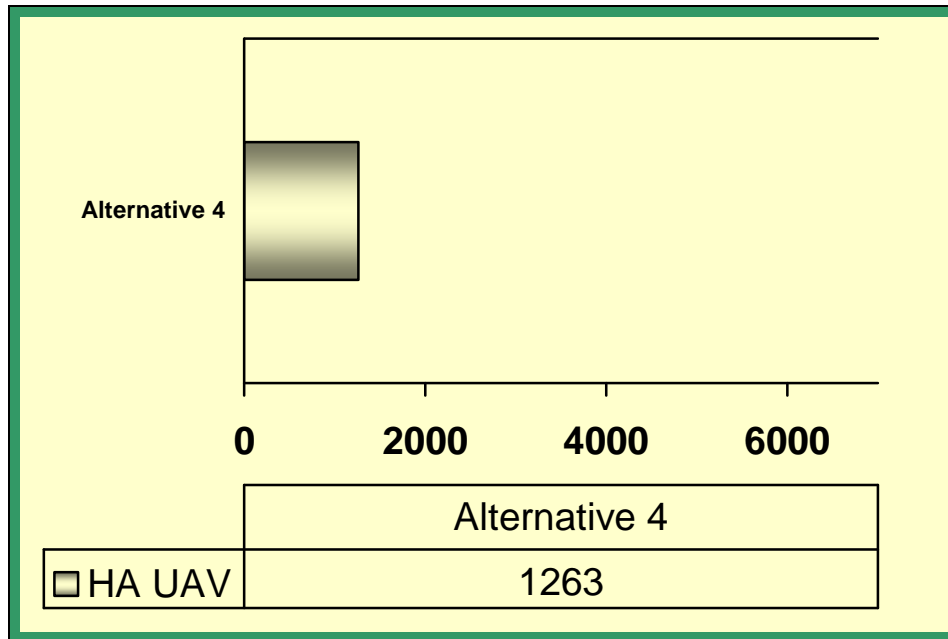


Figure 51. Alternative 4 Effectiveness Score

4. All Medium-Altitude UAS

Another alternative is to invest the entire amount of funding into medium-altitude UAS such as the Sky Warrior. The Sky Warrior costs \$128 million per

¹³¹ United States. Government Accountability Office., 91.

UAS (the UAS consists of 12 aircraft), or \$10.7 million per platform. For \$9.6 billion, 75 Sky Warrior UAS could be purchased (900 individual platforms). The decision has been made to locate the Sky Warrior at the Army division level. With the current plan to purchase 12 UAS, this will be a little more than one per division.¹³² With the 12 platforms per division, it is likely that each of the four BCTs will have use of one or two platforms. 75 UAS, or 900 platforms, would likely be overkill, but would greatly enhance tactical communications and ISR capabilities. Figure 52 shows the overall effectiveness score for the fourth alternative (see Appendix G for effectiveness score calculations). The calculated effectiveness score is based on the average platform effectiveness multiplied by the investment purchase of 900 UAS. This alternative far exceeds the effectiveness scores of the other platforms in alternatives 1-3. This is primarily due to the relative low purchase price of the platform in comparison to the other vehicles. Even though the medium-altitude UAS tallied only an average utility score (20.4) in comparison to the other platforms, the quantity of platforms available within the defined budget constraints is much greater than the other alternatives.

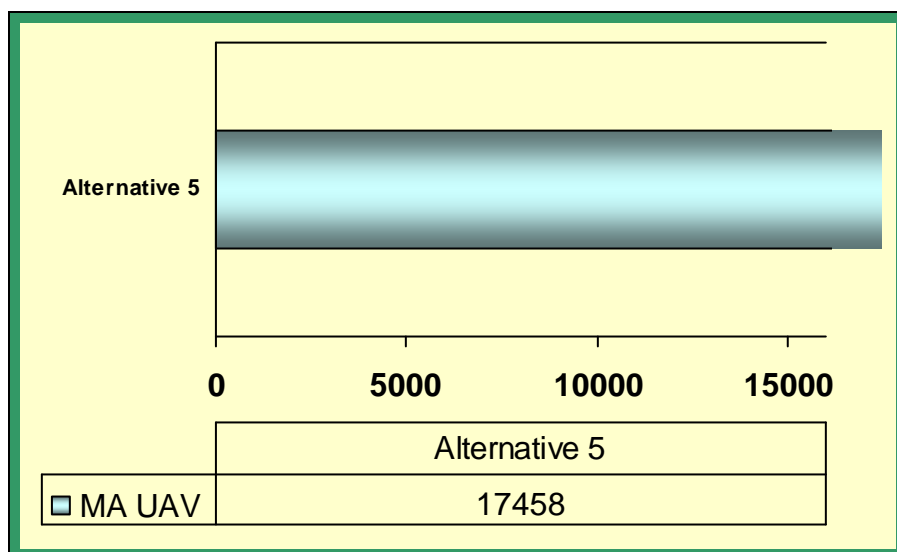


Figure 52. Alternative 5 Effectiveness Score

¹³² United States. Government Accountability Office., 91.

5. Optimized Mix for Scenario A (Most Dangerous Course of Action)

The platform results from Scenario A were used to determine the distribution of funds to each platform. Therefore, with \$9.6 billion the breakout per platform is as follows:

LEO TacSats (.185) would be allocated \$1.78 billion.

HEO TacSats (.219) would be allocated \$2.10 billion. Using the assumptions stated above, this would equal 20 LEO TacSats and 24 HEO. Launch and operations costs will reduce the number of satellites the DoD could buy, but with even half as many set up in an optimized constellation, a significant level of communications and ISR capabilities could be provided.

HAA (.219) would be allocated \$2.10 billion. This would be enough to purchase 42 HAAs. Assuming only 20 are bought, and only 10 (50% in reserve) are in theater at a time, that would be nearly one per BCT. They would likely be controlled at a level above the BCTs, however, with their great ability for persistence, it is likely every tasking a BCT would make would be filled in short order.

Global Hawk (.205) would be allocated \$1.97 billion. This would be enough for 11 Global Hawks. As with the HAA, keeping 50% in reserve would dedicate five the current GWOT efforts overseas.

Sky Warrior (.172) would be allocated \$1.65 billion. This would be enough to purchase over 12 UAS (154 platforms). If 50% were deployed this would give each deployed division two UAS (24 platforms) each. This would be a huge increase in current capabilities.

The effectiveness score depicting the optimized mix for the most dangerous course of action is shown in Figure 53. Overall effectiveness for each platform is based on the number of platforms that can be purchased multiplied by

the effectiveness score of the platform (see Appendix G for effectiveness score calculations). The total effectiveness for alternative 5 is the combination of the effectiveness scores of each platform.

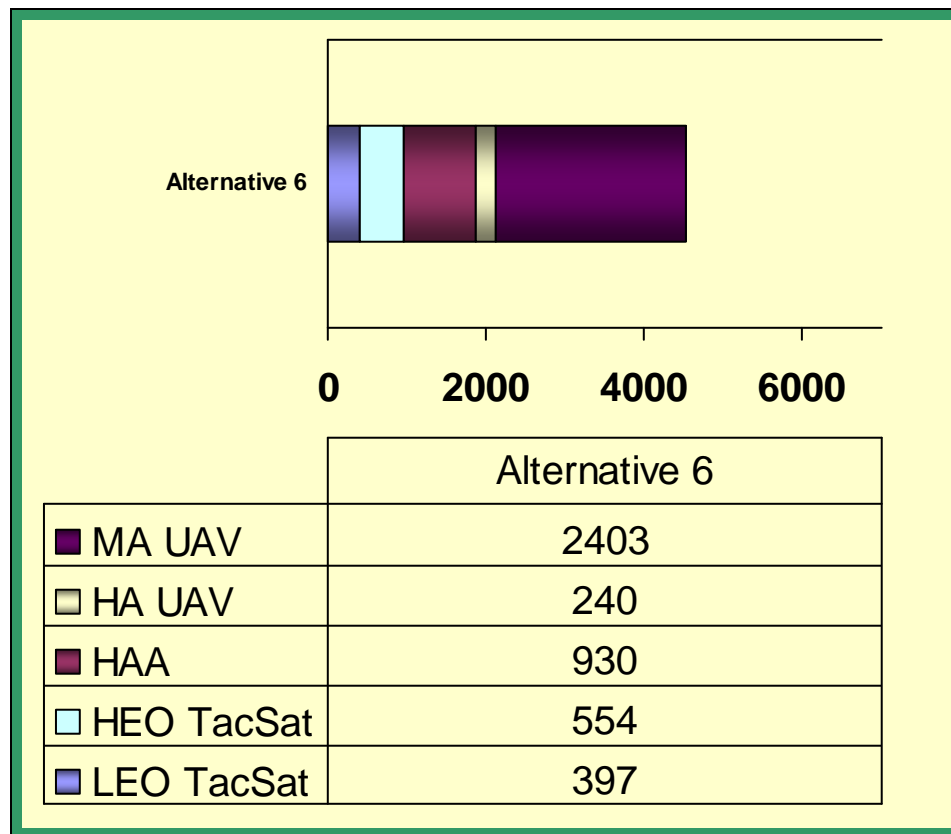


Figure 53. Alternative 6 Effectiveness Score

6. Optimized Mix for Scenario B

Using the same method used for Scenario A, the funds in Scenario B would be distributed in the following manner:

LEO TacSats (.099) would be allocated \$0.95 billion. This would be enough for 11 LEO TacSats.

HEO TacSats (.135) would be allocated \$1.30 billion. This would be enough for 15 HEO TacSats.

HAA (.316) would be allocated \$3.03 billion. This would be enough for 61 HAAs.

Global Hawks (.246) would be allocated \$2.36 billion. This would be enough for 13 Global Hawks.

Sky Warrior (.204) would be allocated \$1.96 billion. This would be enough for over 15 Sky Warrior UAS (183 platforms).

The effectiveness score depicting the optimized mix for scenario B is shown in Figure 54. Overall effectiveness for each platform is based on the number of platforms that can be purchased multiplied by the effectiveness score of the platform (see Appendix G for effectiveness score calculations). The total effectiveness for alternative 6 is the combination of the effectiveness scores of each platform.

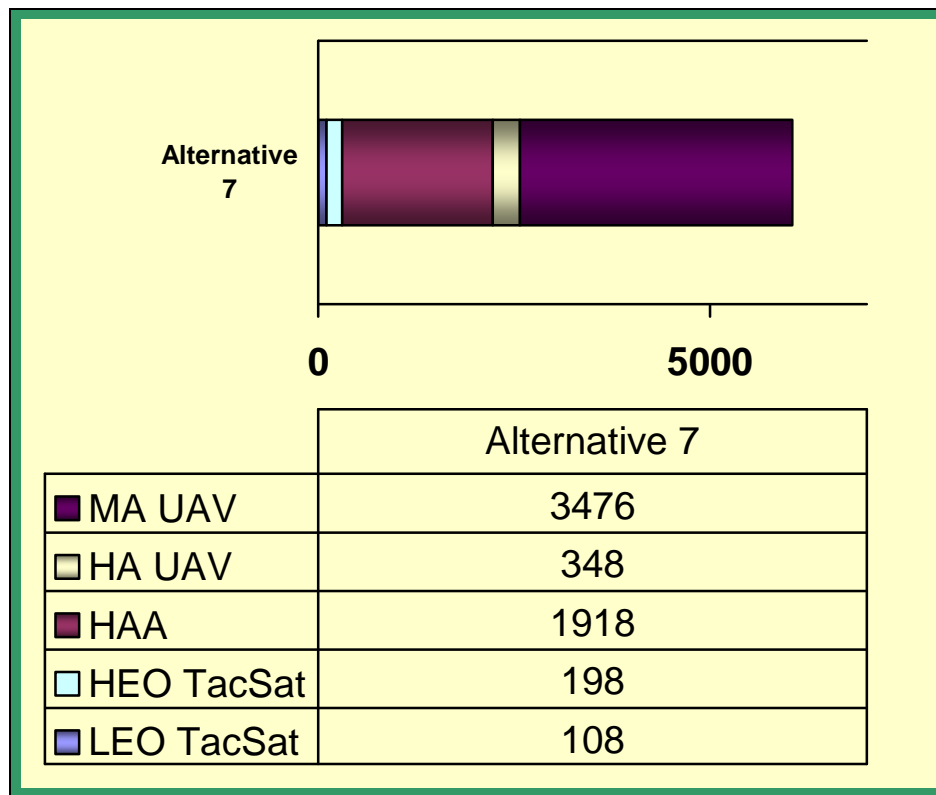


Figure 54. Alternative 7 Effectiveness Score

7. Optimized Mix for Scenario C (Most Likely Course of Action)

Using the same method used for Scenarios A and B, the funds in Scenario C would be distributed in the following manner:

LEO TacSats (.097) would be allocated \$0.93 billion. This would be enough for 11 LEO TacSats.

HEO TacSats (.165) would be allocated \$1.58 billion. This would be enough for 18 HEO TacSats

HAA (.288) would be allocated \$2.76 billion. This would be enough for 55 HAAs.

Global Hawks (.231) would be allocated \$2.22 billion. This would be enough for 12 Global Hawks.

Sky Warrior (.219) would be allocated \$2.10 billion. This would be enough for 16 Sky Warrior UAS (196 platforms).

The effectiveness score depicting the optimized mix for the most likely course of action is shown in Figure 55. Overall effectiveness for each platform is based on the number of platforms that can be purchased multiplied by the effectiveness score of the platform (see Appendix G for effectiveness score calculations). The total effectiveness for alternative 7 is the combination of the effectiveness scores of each platform.

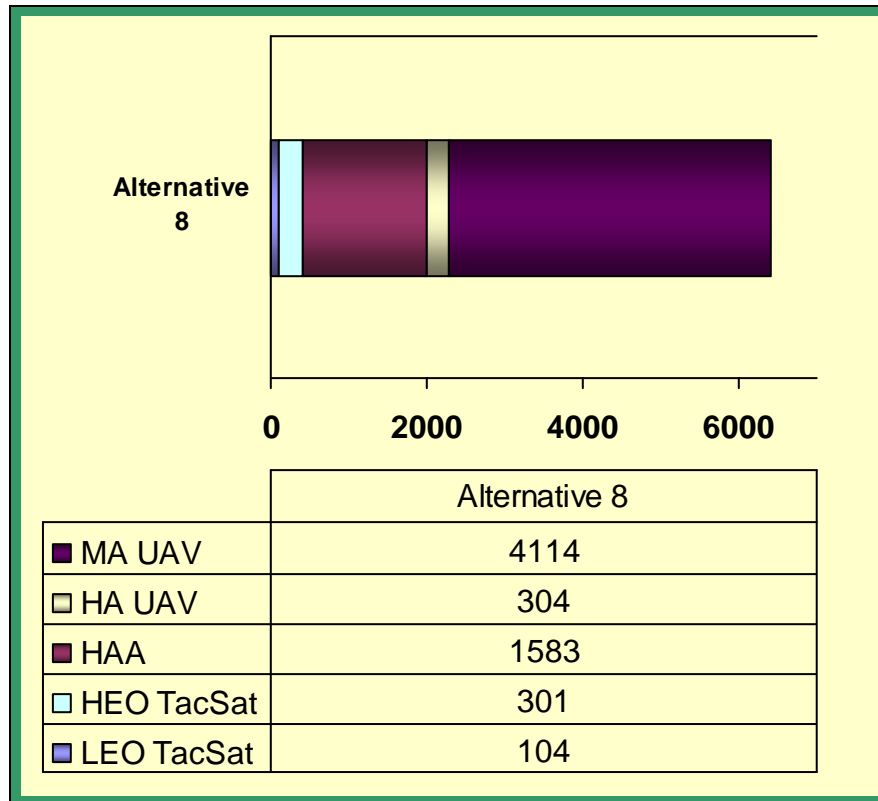


Figure 55. Alternative 8 Effectiveness Score

8. Mix for Evenly Weighted Scenarios

Using the same method used for Scenarios A, B, and C, the funds in this mix would be distributed in the following manner:

LEO TacSats (.127) would be allocated \$1.22 billion. This would be enough for 14 LEO TacSats.

HEO TacSats (.173) would be allocated \$1.66 billion. This would be enough for 19 HEO TacSats.

HAA (.274) would be allocated \$2.63 billion. This would be enough for 53 HAAs.

Global Hawks (.227) would be allocated \$2.18 billion. This would be enough for 12 Global Hawks.

Sky Warrior (.198) would be allocated \$1.90 billion. This would be enough for over 14 Sky Warrior UAS (178 platforms).

The effectiveness score when investment in alternative platforms is based upon an even weighting of all three scenarios is shown in Figure 56. Overall effectiveness for each platform is based on the number of platforms that can be purchased multiplied by the average effectiveness score of the platform (see Appendix G for effectiveness score calculations). The total effectiveness for alternative 8 is the combination of the effectiveness scores of each platform.

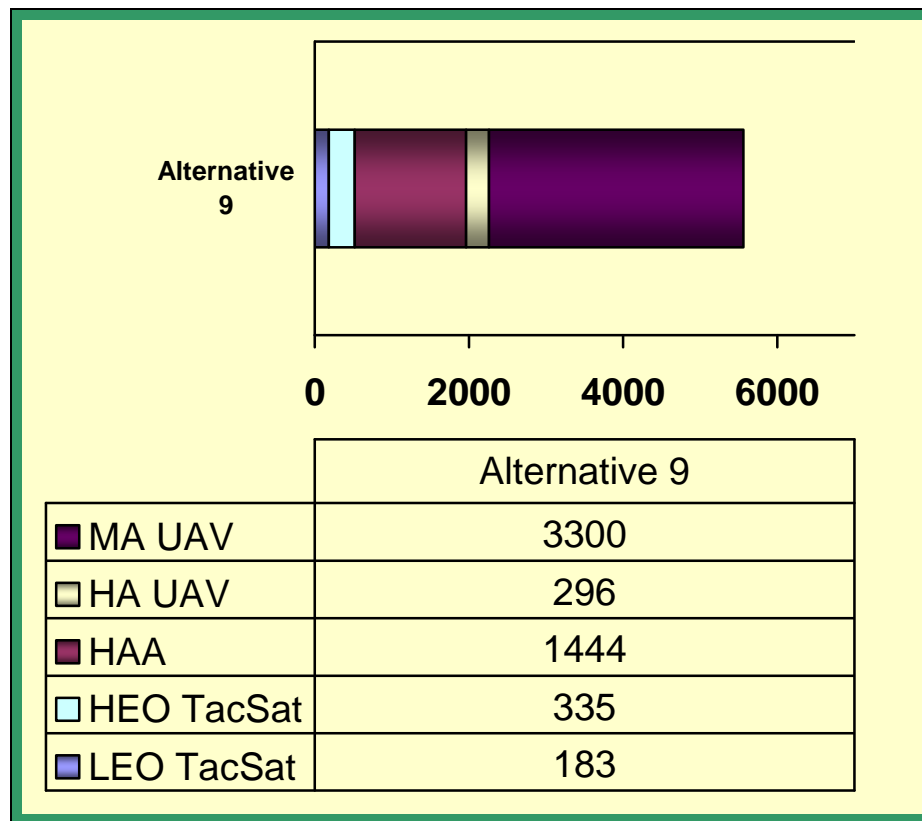


Figure 56. Alternative 9 Effectiveness Score

9. Mix for Scenario A Weighted the Highest

Using the same method used previously, the funds in this mix would be distributed in the following manner:

LEO TacSats (.150) would be allocated \$1.44 billion. This would be enough for 17 LEO TacSats.

HEO TacSats (.194) would be allocated \$1.83 billion. This would be enough for 21 HEO TacSats.

HAA (.252) would be allocated \$2.42 billion. This would be enough for 48 HAAs.

Global Hawks (.219) would be allocated \$2.10 billion. This would be enough for 12 Global Hawks.

Sky Warrior (.188) would be allocated \$1.80 billion. This would be enough for 14 Sky Warrior UAS (169 platforms).

The effectiveness score when investment in alternative platforms is based upon an even weighting of all three scenarios is shown in Figure 57. Overall effectiveness for each platform is based on the number of platforms that can be purchased multiplied by the average effectiveness score of the platform (see Appendix G for effectiveness score calculations). The total effectiveness for alternative 10 is the combination of the effectiveness scores of each platform.

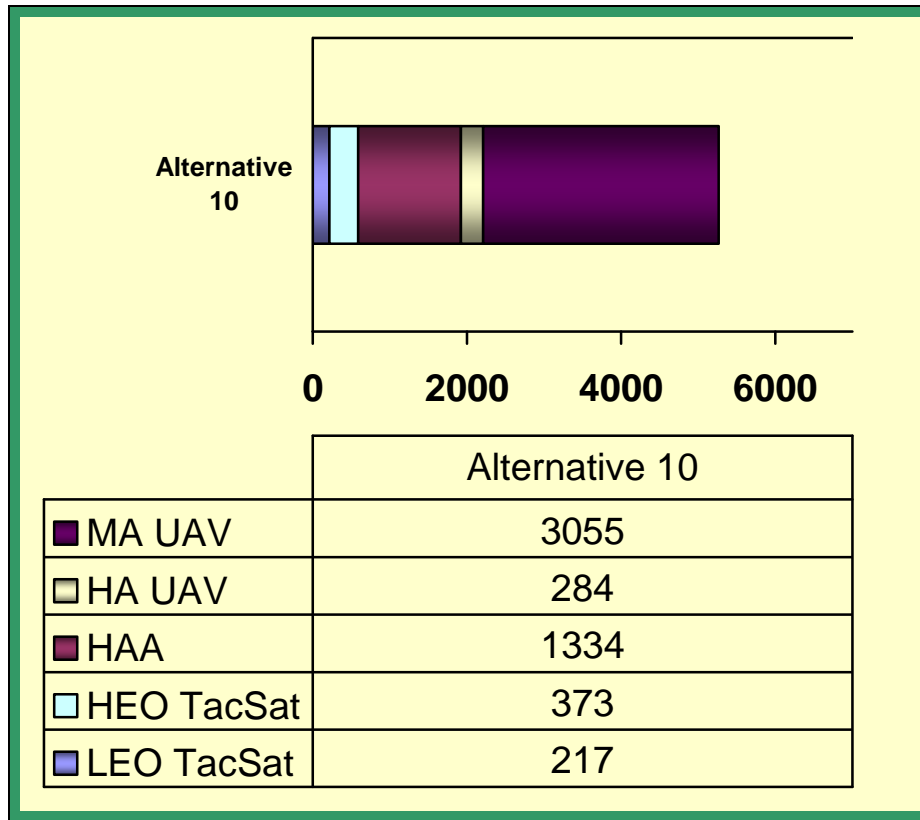


Figure 57. Alternative 10 Effectiveness Score

10. Mix for Scenario B Weighted the Highest

Using the same method used previously, the funds in this mix would be distributed in the following manner:

LEO TacSats (.116) would be allocated \$1.11 billion. This would be enough for 13 LEO TacSats.

HEO TacSats (.158) would be allocated \$1.52 billion. This would be enough for 17 HEO TacSats.

HAA (.291) would be allocated \$2.79 billion. This would be enough for 56 HAAs.

Global Hawks (.235) would be allocated \$2.26 billion. This would be enough for 13 Global Hawks.

Sky Warrior (.200) would be allocated \$1.92 billion. This would be enough for more than 14 Sky Warrior UAS (179 platforms).

The effectiveness score when investment in alternative platforms is based upon an even weighting of all three scenarios is shown in Figure 58. Overall effectiveness for each platform is based on the number of platforms that can be purchased multiplied by the average effectiveness score of the platform (see Appendix G for effectiveness score calculations). The total effectiveness for alternative 11 is the combination of the effectiveness scores of each platform.

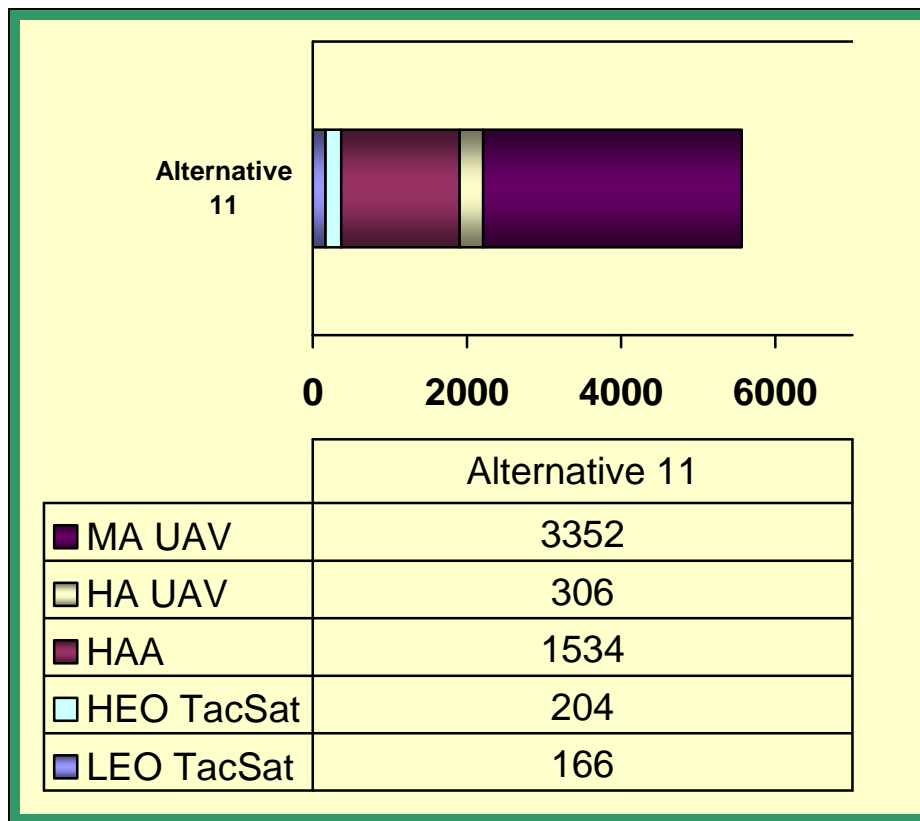


Figure 58. Alternative 11 Effectiveness Score

11. Mix for Scenario C Weighted the Highest

Using the same method used previously, the funds in this mix would be distributed in the following manner:

LEO TacSats (.115) would be allocated \$1.10 billion. This would be enough for 13 LEO TacSats.

HEO TacSats (.170) would be allocated \$1.63 billion. This would be enough for 19 HEO TacSats.

HAA (.280) would be allocated \$2.69 billion. This would be enough for 54 HAAs.

Global Hawks (.229) would be allocated \$2.20 billion. This would be enough for 12 Global Hawks.

Sky Warrior (.206) would be allocated \$1.98 billion. This would be enough for over 15 Sky Warrior UAS (185 platforms).

The effectiveness score when investment in alternative platforms is based upon an even weighting of all three scenarios is shown in Figure 59. Overall effectiveness for each platform is based on the number of platforms that can be purchased multiplied by the average effectiveness score of the platform (see Appendix G for effectiveness score calculations). The total effectiveness for alternative 12 is the combination of the effectiveness scores of each platform.

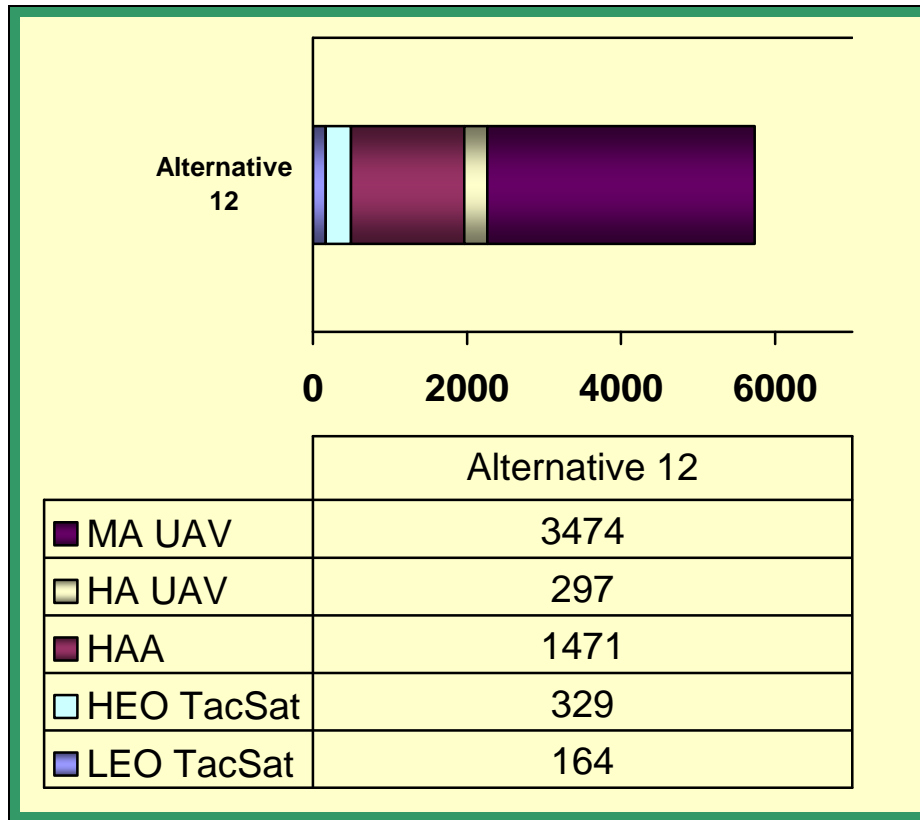


Figure 59. Alternative 12 Effectiveness Score

12. Equal Investment in Platforms for Budget of \$9.6 Billion

Using the investment budget of \$9.6 billion and evenly dividing the money among alternative platforms, the funds in this mix would be distributed in the following manner:

LEO TacSats (.200) would be allocated \$1.92 billion. This would be enough for 22 LEO TacSats.

HEO TacSats (.200) would also be allocated \$1.92 billion. This would be enough for 22 HEO TacSats

HAA (.200) would also be allocated \$1.92 billion. This would be enough for 38 HAAs.

Global Hawks (.200) would also be allocated \$1.92 billion. This would be enough for 11 Global Hawks.

Sky Warrior (.200) would also be allocated \$1.92 billion. This would be enough for over 14 Sky Warrior UAS (179 platforms).

The effectiveness score when investment in alternative platforms is based upon an even distribution of \$9.6 billion is depicted Figure 60. Overall effectiveness for each platform is based on the number of platforms that can be purchased multiplied by the average effectiveness score of the platform (see Appendix G for effectiveness score calculations). The total effectiveness for alternative 13 is the combination of the effectiveness scores of each platform.

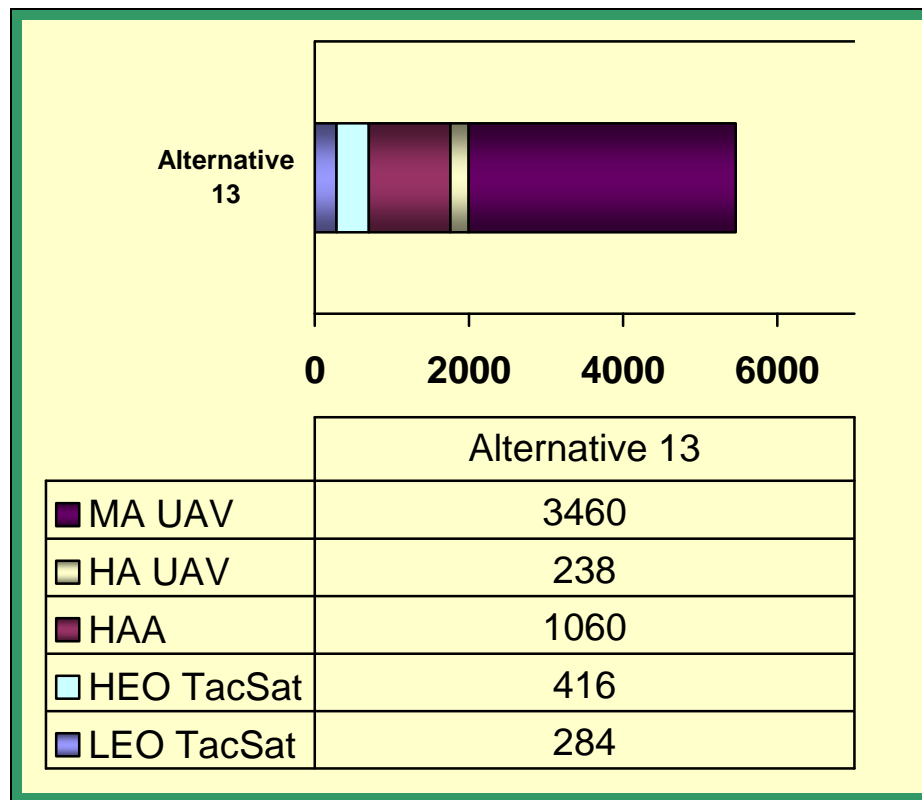


Figure 60. Alternative 13 Effectiveness Score

13. Equal Investment in Platforms for Budget of \$4.8 Billion

Using the investment budget of \$4.8 billion and evenly dividing the money among alternative platforms, the funds in this mix would be distributed in the following manner:

LEO TacSats (.200) would be allocated \$0.96 billion. This would be enough for 11 LEO TacSats.

HEO TacSats (.200) would also be allocated \$0.96 billion. This would be enough for 11 HEO TacSats

HAA (.200) would also be allocated \$0.96 billion. This would be enough for 19 HAAs.

Global Hawks (.200) would also be allocated \$0.96 billion. This would be enough for five Global Hawks.

Sky Warrior (.200) would also be allocated \$0.96 billion. This would be enough for over seven Sky Warrior UAS (90 platforms).

The effectiveness score when investment in alternative platforms is based upon an even distribution of \$4.8 billion is depicted Figure 61. Overall effectiveness for each platform is based on the number of platforms that can be purchased multiplied by the average effectiveness score of the platform (see Appendix G for effectiveness score calculations). The total effectiveness for alternative 14 is the combination of the effectiveness scores of each platform. The results shows that the calculations and effectiveness are indeed linear and that you will get $\frac{1}{2}$ the effectiveness of the \$9.6 billion investment.

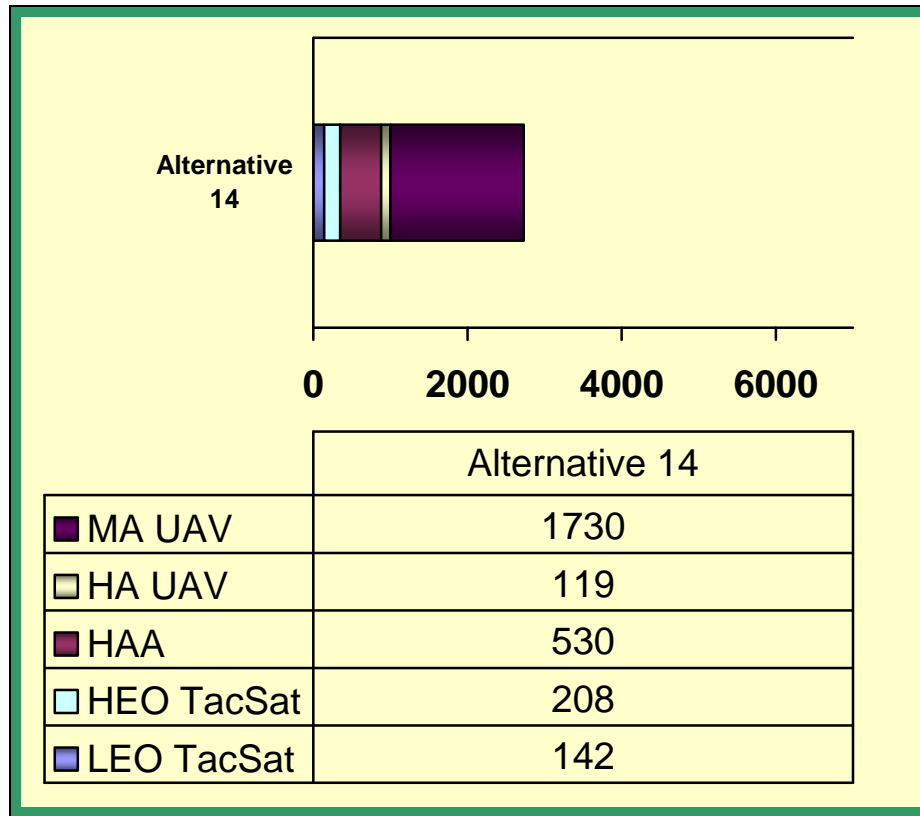


Figure 61. Alternative 14 Effectiveness Score

14. Equal Investment in Platforms for Budget of \$1 Billion

Using the investment budget of \$1 billion and evenly dividing the money among alternative platforms, the funds in this mix would be distributed in the following manner:

LEO TacSats (.200) would be allocated \$200 million. This would be enough for two LEO TacSats.

HEO TacSats (.200) would also be allocated \$200 million. This would be enough for two HEO TacSats

HAA (.200) would also be allocated \$200 million. This would be enough for two HAAs.

Global Hawks (.200) would also be allocated \$200 million. This would be enough for one Global Hawks.

Sky Warrior (.200) would also be allocated \$0.96 billion. This would be enough for a little over one Sky Warrior UAS (19 platforms).

The effectiveness score when investment in alternative platforms is based upon an even distribution of \$1 billion is depicted Figure 62. Overall effectiveness for each platform is based on the number of platforms that can be purchased multiplied by the average effectiveness score of the platform (see Appendix G for effectiveness score calculations). The total effectiveness for alternative 15 is the combination of the effectiveness scores of each platform. This shows the total effectiveness that can be achieved for a more modest investment. The total effectiveness for alternative 15 is the combination of the effectiveness scores of each platform. The results shows that the calculations and effectiveness are indeed linear and that you will get 1/10 the effectiveness of the \$9.6 billion investment.

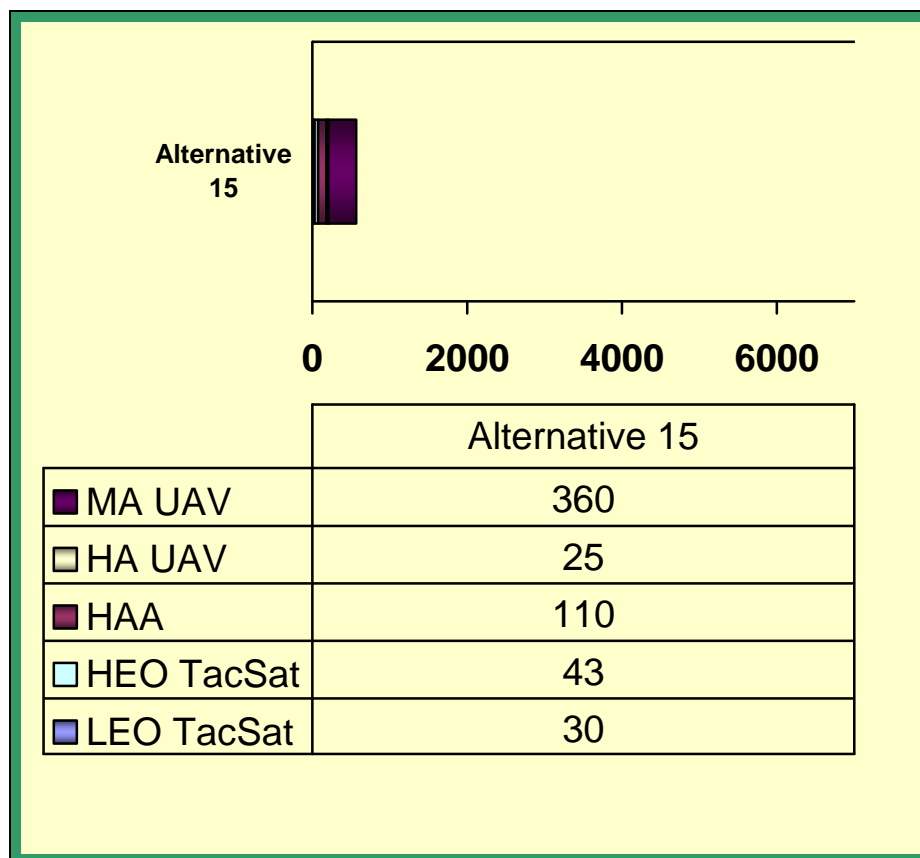


Figure 62. Alternative 15 Effectiveness Score

B. EVALUATION OF ALTERNATIVES

Figure 60 compares the effectiveness score of all 15 alternatives. Alternative 5 immediately jumps out as having the highest effectiveness score by a very wide margin. Its score is nearly 11,000 points higher than the next highest alternative (alternative 8). The reason the score is so high is that you can buy nearly 900 Sky-Warriors for \$9.6 billion. Theoretically, this may seem like a feasible plan. In reality, scrapping all other programs and investing all platform funding in the Sky-Warrior program is not a realistic way to invest DoD resources or maximize ISR and communications platform capability. Although the medium altitude UAS has a modest effectiveness score in comparison to the other platforms, the much cheaper price per platform may lead the decision maker to believe he can purchase his way to unparalleled capability. This course of action would eliminate the unique capabilities that other platforms bring to the fight that the Sky-Warrior is incapable of adequately providing. It is important to note, however, that the effectiveness score for any alternative will increase most when a majority of investment is used to purchase more medium altitude UAS.

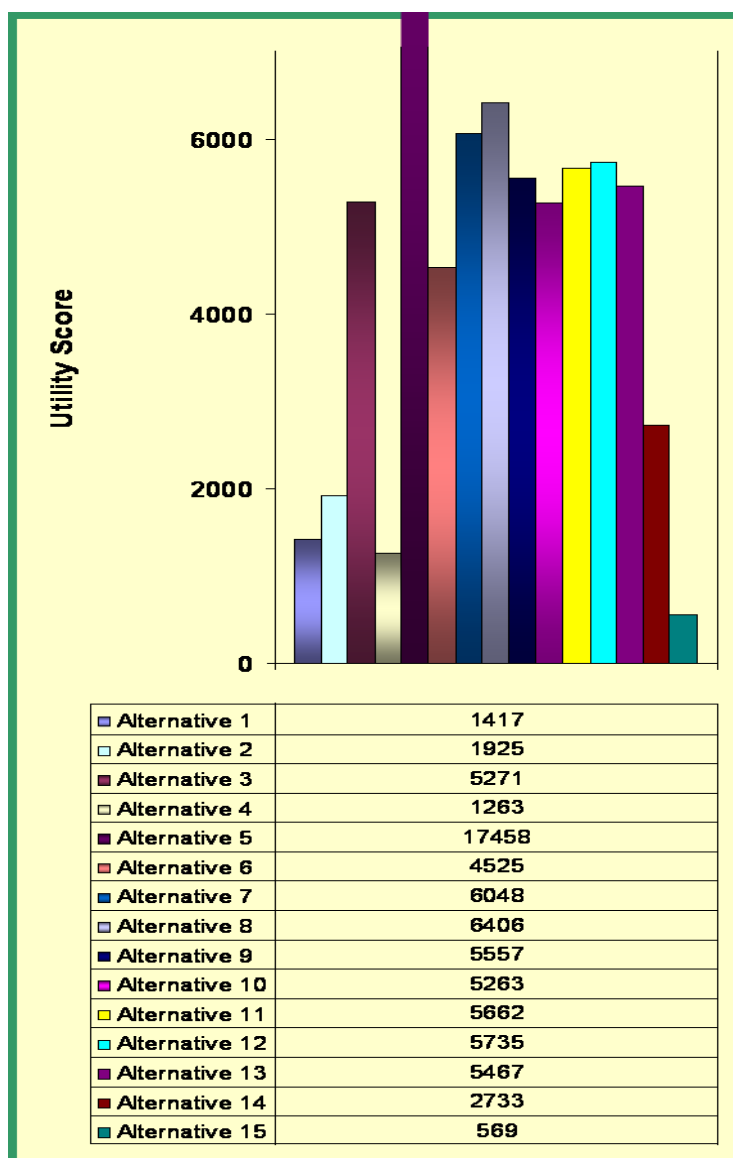


Figure 63. Effectiveness Score Comparison of Alternatives

Alternative 4 is interesting in that it gets such a low effectiveness score. It barely gets more than twice the effectiveness of alternative 12 for more than nine times the budget. The reason for this is that it is the opposite situation in alternative 5. The Global Hawks are so expensive that you can only buy a few of them, even with a large budget, which drops the overall effectiveness of the fleet. The decision maker may be inclined to eliminate this platform based on its low effectiveness score and high price. However, for responsiveness on a global scale, the high altitude UAS are currently unparalleled.

Since investment in a single platform is an unrealistic option, the next obvious course for evaluation is to analyze the various alternatives that use combinations of platforms to determine which will provide the most effectiveness. The next highest scoring alternative is 8. Alternative 8 is the optimized mix of platforms for Scenario C, the most likely course of action. This alternative provides a good mix of all platforms examined in accordance with the platform weights established by the comparative analysis. There is heavy investment in the medium altitude UAS in this alternative, which, as stated before, tends to drive up the total effectiveness score.

For the sake of comparison, alternatives 10, 11, and 12 examine the impact on effectiveness as the investment budget for alternatives drops. As expected, if the money is evenly divided among the platforms the effectiveness score of the alternative drops proportionately in these alternatives. Most interesting may be a closer look at the amount of effectiveness that can be obtained by choosing alternative 12, which shows the lowest effectiveness score with least amount of investment.

Using the worst-case scenario (high intensity combat without air superiority) as an example, we attempted to identify what level of effectiveness alternative 15 would provide to the commander on the ground for communications and ISR. In other words, would the smallest investment used in our study provide the necessary capability the commander on the ground would require in this scenario? To use this analogy, we first needed to identify what requirements the commander would have from his communications and ISR platforms. They include:

1. Continuous communications prior to the initiation of offensive operations with his battlefield commanders;
2. Continuous ISR coverage of "close" objectives prior to the initiation of operations;
3. Daily ISR coverage updates of 2-3 "deep" objectives every day for future ops planning;

4. The ability to provide continuous communications on the move after crossing the line of departure;
5. Continuous "eyes forward" for indications and warnings of enemy actions/counterattack at the onset of operations from both "close" and "deep" targets;
6. The ability to surge ISR assets onto new targets of opportunity as they arise without losing coverage of previously identified objectives.

We can assume that this level of operation would involve, at a minimum, units with at least some organic medium-altitude UAS assets (Army division or Marine Expeditionary Unit), and that all other assets for support would be tasked accordingly. With these assumptions in place, how well would the commander on the ground be supported with the \$1 billion investment budget?

With two high altitude airships, each with a footprint that would cover all of North Korea while operating at normal altitude, continuous communications prior to the initiation of offensive operations would easily be covered. If these assets were not yet in place, the commander with two HEO TacSats could get four hours of communications coverage each day, and incorporate his single Global Hawk to provide coverage during any gaps he may have until the HAAs arrive in theater.

Since the HAA platforms at his disposal are capable of providing both communications and ISR, the commander would be able to use their sensors to provide continuous ISR coverage of "close" objectives before the initiation of offensive operations. Although these platforms would be far back from the forward edge of the fight, their sensor footprint would easily access the enemy territory that encompasses initial maneuver objectives. Organic UAS platforms could be utilized to provide any additional sensor coverage of objectives the commander may desire.

For targets outside the access area of the HAAs or UAS platforms, the commander would have two LEO TacSat ISR platforms at his disposal for this scenario. With the capability these assets provide, deeper targets outside the

access area of airborne platforms could be covered for future operations. After crossing the line of departure, the commander would be able to see enemy reactions and gauge his decisions on critical maneuver and reinforcements based on enemy actions well beyond the sensing capability of his organic assets.

For continuous communications on the move, numerous assets would be at the commander's disposal for the proposed budget. As friendly forces moved across the battlefield and air space coordination areas were established overhead, airborne assets could move in conjunction with friendly maneuver to provide maximum coverage. Likewise, the medium-altitude UAS platforms, like the Sky Warrior, could provide communications on the move for forces maneuvering toward objectives, establishing an overhead communications network that maintained a constant footprint over the areas most in need.

After the initiation of offensive operations, the ground forces commander would be able to receive regular coverage of deep targets from both his TacSat ISR platforms and Global Hawk UAS. Simultaneously, if targets of opportunity became available and the commander needed to surge assets to provide ISR coverage or communications for distributed operations (while maintaining his continued capabilities in the main battle area), the responsiveness of the medium-altitude UAS platforms would allow him to provide maneuvering forces with the necessary coverage without slowing the tempo of his primary force.

As one can see from the closer look at the alternative with the least amount of investment, the effectiveness that is available to the commander in the most dangerous course of action is actually quite abundant. With the correct mix of only a few platforms, the overall ISR and communications capability that he can bring to bear is formidable. Drawing on the individual strengths of the platforms in our study and understanding their limitations, an analysis of the potential capability that the correct mix of platforms can bring to the fight can help commanders utilize these assets to their full potential and help decision makers determine the correct mix of investment to support the warfighter.

In conclusion, based on the platform effectiveness scores in each scenario, the investment in the LEO TacSat platform should be minimal at best. The only capability that it brings to the table above the other options is in its performance of access in scenario A. If the warfighter is truly pressed for ISR inside denied territory that other platforms cannot reach, then the LEO TacSat could be the only option available. However, for the amount of investment involved to provide this capability, decision makers conducting preparations in the event of scenario A could task national assets to provide at least as much if not more access capability than the LEO TacSat. The investment for the platform could then be used to purchase additional HAA and UAS platforms. Outside of scenario A, the LEO TacSat provides little effectiveness that could not be attained by the other platforms.

Likewise, limited investment should be used to purchase the HEO TacSat platform in the event the warfighter needs support in scenario A. The platform provides full access in scenario A with greater endurance than the LEO platform, making it a useful asset for the warfighter in this scenario. However, in the other scenarios the HEO TacSat has little effectiveness that it brings to the warfighter that could not be covered by additional investment in the other platforms.

Although the medium altitude UAS shows modest effectiveness scores in comparison to some of the other platforms, its responsiveness to the warfighter is unmatched. This capability provides the ground commander the ability to surge assets to support critical needs far above the other platforms. Combined with its relatively cheap per-platform cost, the benefit of this platform's utility in all three scenarios makes it a force multiplier to the warfighter.

The utility of the HAA and high altitude UAS stand out most in this study. By far, the HAA provided the most per-platform utility to the warfighter in this study. Its overwhelming endurance and ability to conduct multiple missions from high altitude, provides the warfighter with a tactical advantage for relatively low cost (in comparison to the other platforms). Combined with the proven capability of the high altitude UAS, which provides the responsiveness the HAA is lacking,

these two platforms allow the warfighter the advantage of being prepared for each of the scenarios (worst case and most likely) used in our study.

C. HOW CHANGES IN THE MOES COULD IMPACT THE STUDY

The MOEs are the foundation of the study and by changing them the study itself would significantly change. Many alternative MOEs were explored for this study and reasons for not including them were explained in Chapter III. Additionally, the authors received some feedback from the survey audience on some of their opinions regarding the MOEs that might be useful to consider.

One survey respondent suggested that access should not be an MOE because without access, coverage could not take place and therefore only coverage was necessary. The authors believe he was partially correct in that you do need access for coverage. However, in our imperfect world, we frequently do not have access to places that we want to look at. Therefore, the ability to gain access is necessary and a platform that can do that provides a significant advantage over platforms that cannot.

Some respondents did not think that the responsiveness MOE was discreet enough, and that it more closely resembled a mix of elements that could have been MOEs themselves. Others thought that responsiveness should have been called agility instead. However, no one thought that it was an irrelevant measure or that it did not belong in the trade space at all.

One respondent thought that the communications and ISR missions are so different that they should be separated and evaluated independently. This is a valid suggestion, as the mission set is not usually combined. It is true that most UAS are only geared toward the ISR mission. It is also true that most satellites are specifically configured to conduct ISR or communications, but rarely both. However, there is no physical reason why both missions cannot be conducted by the same platform in most circumstances. The decisions made in the mission analysis for the satellite (including the orbitology for the platform) are

usually designed to support the optimization of either mission, but this does not preclude the possibility, under certain circumstances, that a satellite could be both an ISR and communications platform.

Some suggested that the definition of the coverage MOE was too similar to the definition of coverage rate. This may be a valid statement. The authors made an effort to ensure a clear distinction between the Access and Coverage MOEs to eliminate confusion. Additionally, it is inherently difficult to define a figure of merit for coverage. SMAD lists no less than five different examples. Additionally, it warns, “Statistical analysis of inherently non-statistical data, such as orbit coverage, can lead to dramatically incorrect conclusions”.¹³³ Therefore, there may be some debate about what the best metric should be used for coverage. However, the authors believe that the chosen metric best reflects what a ground commander want to know – how long until I get what I asked for.

Finally, some respondents thought that the definition for endurance used in the study more closely resembled persistence or availability. This is incorrect. Persistence is in fact what the DoD is trying to achieve with a variety of platforms. Endurance more accurately defines how long a single platform can conduct its individual mission.

D. HOW CHANGES IN THE SURVEY AUDIENCE COULD IMPACT THE STUDY

The survey audience is an important piece of the survey. Their opinions shape the weights each MOE has with respect to the other MOEs. Their experiences, education, understanding of the MOEs within the context of the study, and preconceived opinions of the MOEs all influence the MOE weights and therefore the outcome of the analysis once platform metrics are applied. In an ideal study, the survey audience would consist of Army and Marine senior commanders, intelligence and operations officers with at least one tour in Iraq or Afghanistan. This population would have recent direct experience with

¹³³ Larson and Wertz, 173.

successes or failures with current communications and ISR collection capabilities. Most of the population would also likely have some experience with the success or failure of current UAS platforms to deliver the type and quality of ISR products requested.

This is not to say that the conclusions of the survey population for this thesis should be discounted. The survey population included several academic professors with extensive military experience, and a number of Army and Marine field grade officers, several with experience in Iraq. The population used provides a well-rounded and educated group with a good understanding of the problem and similar experiences to draw from. The results were well within the consistency allowances of the AHP making the data mathematically acceptable. Additionally, the survey results were generally along the lines of what the authors predicted the outcome would be.

E. AREAS FOR FURTHER STUDY AND ANALYSIS

There are a number of different areas in this study that could have been expanded and explored further. First, additional unclassified platforms could have been included in the pool of those considered. Specifically, additional high-altitude long-endurance experiments such as the Global Observer might be useful to look at. Foreign projects were not looked at and may add some value. Additionally, there are also a number of free-floating balloon systems that have shown some limited success and may be useful to consider. This study should be repeated in a couple of years after the HAA prototype, Sky-Warrior, TacSat-4, and the Global Hawk RQ-4B have been completed and fully tested. After first flight, a better understanding of their potential capabilities and costs will be better understood.

For reasons explained earlier, this study did not focus on the platform sensors but on the platforms themselves. If this were changed, and if a platform's sensor payload far exceeded the capabilities of other platforms' payloads then this could give it an advantage. This may apply to the HAA where

its payload mass and volume are considerably larger than the other platforms. The quality of the HAA sensor might not be significantly greater, but the quantity might be. This would give it the advantage of providing coverage more quickly and possibly add new capabilities not considered on current UAS because of their lack of mass or volume.

Additional elements that may warrant study are risk factors such as performance, cost, schedule, and budget for all representative platforms. The Global Hawk is the only platform that has actually seen action, but the new upgraded version of the Global Hawk, the Global Hawk RQ-4B, has encountered some developmental issues and the TacSats continue to encounter launch delays.¹³⁴ Therefore, all the platforms discussed could meet setbacks that could alter their cost or estimated delivery date. These risk factors will be different for each platform and may influence the amount of time and investment the DoD will devote to them. Additional study on these factors would determine the platforms with the greatest assumed risk and would alter the platforms score if risk were considered as a MOE.

An additional classified study could be conducted using the same processes but including current and planned national space assets, the U-2, and other classified aerial platforms and sensors. This would broaden the platform base and possibly reveal a new best, or worst, platform. It would also allow for a better assessment of the classified capabilities of the platforms currently in the study.

Additionally, there are alternate methods of applying the AHP such as variations of the AHP developed by Dr. Francois Melese, Professor of the Naval Postgraduate School Defense Resources Management Institute (DRMI). This method begins with creating an objective hierarchy. The objective is defined by the goals, objectives or performance of the object of the study. MOEs are developed that best represent the objective. MOEs are weighted with a survey of

¹³⁴ United States. Government Accountability Office. 92.

experts in the field. Once the survey results are tabulated, an additional step of going back to the survey population with some metrics for each MOE and determining how much of one MOE they would be willing to sacrifice for a gain in another MOE when all other MOEs are held constant is taken. This method requires additional time from each respondent but would insure consistency or reveal inconsistency in a survey respondent's initial answers. This method might also offer additional insights into what the respondents truly value and may cause the respondents to alter their initial conclusions and answers.¹³⁵

Next, alternatives are defined with various systems or capabilities that can currently meet or fulfill most of the objective. To compare these capabilities or systems, this method creates an ideal system by using the best characteristics from all the systems and then measuring each system against the ideal. This would allow you to see how much of the ideal you are getting with an individual platform. Next, several alternatives are created with various mixes of systems in an effort to get as close to the ideal as possible.

Then, a likely budget is defined. The effectiveness of each mix is compared to the cost of each mix. The goal is to choose the most effective mix that meets budget constraints. Finally, other factors such as schedule and risks are factored into the decision. Risks include performance, cost, schedule slippages and budget changes.

F. SUMMARY

In summary, this study conducted a detailed cost-effectiveness analysis on five potential systems for use as a persistent communications and ISR platform. In particular, the thesis authors conducted a survey to determine how to weight platform criteria in various militarily relevant scenarios. Next, it measured the performance of each platform against the criteria and used the personal experiences of the authors to validate how they would most likely be

¹³⁵ Francois Melese, Discussion on Variations of the Analytical Hierarchy Process, 2008.

employed to aid in ground tactical operations. The results were then combined in the mathematically rigorous Analytical Hierarch Process to determine how well each platform did. The cost of the platforms were then analyzed and applied to the AHP to determine an optimal mix of platforms for each scenario. The scenario weights were adjusted to allow for preference of one scenario over the others. This showed the cost for the required platforms and the associated level of effectiveness for each scenario. A number of mixed platform alternatives were examined to determine the most effective mix of platforms to be employed for a set cost. Alternative 8, the optimized mix for Scenario C, (low intensity operations with air superiority and the most likely course of action) had the highest effectiveness score when all platforms were employed.

APPENDIX A: PLATFORM MOE PROS/CONS

| Responsiveness | |
|-----------------------|--|
| TacSats | <ul style="list-style-type: none"> • Pros <ul style="list-style-type: none"> – No forward deployed footprint required – Does not necessarily require new tasking to respond – In a new geographical area, may be fastest to respond – Possesses ability to respond to multiple new missions due to world wide access • Cons <ul style="list-style-type: none"> – Possible delay to area of interest until next pass – May require inclination change (satellite may not be capable of doing) – Without ORS, slow potential for timely response to lost asset – Once launched, no ability to change payloads for new missions – Orbital parameters may limit response time |
| HAAs | <ul style="list-style-type: none"> • Pros <ul style="list-style-type: none"> – No forward deployed footprint required – Potentially short response timeline for launch or new/replacement asset – Response time to new mission area could be short (geographic dependent) – Ability to change payloads for new mission requirements • Cons <ul style="list-style-type: none"> – Not capable of operating in all latitudes due to high altitude wind speed – Transit time to area of interest could take longer than desirable – Payload change could be time consuming – Vulnerable to peer/near-peer adversaries when no air superiority established |
| HA UAVs | <ul style="list-style-type: none"> • Pros <ul style="list-style-type: none"> – Quick response to new missions/lost assets in same geographic area – Quick response to new missions outside same geographical area – No forward deployed footprint required (but may have limited endurance without) – Capable of changing payloads for new missions • Cons <ul style="list-style-type: none"> – Vulnerable to peer/near-peer adversaries when no air superiority established |
| MA UAVs | <ul style="list-style-type: none"> • Pros <ul style="list-style-type: none"> – Quick response to new missions/lost assets in same geographic area – Due to asset level of control (Division), may provide quicker responsiveness to tactical targets – Capable of changing payloads for new missions • Cons <ul style="list-style-type: none"> – Vulnerable to adversary aerial defenses; would require air superiority – Response to missions in new geographic area requires forward deployed support |

| Access | |
|---------|---|
| TacSats | <ul style="list-style-type: none"> • Pros <ul style="list-style-type: none"> – Global access (within constraints of orbital mechanics) – Not dependent on denied vs. undenied territory – No weather impact on access • Cons <ul style="list-style-type: none"> – Inclination in LEO may limit access |
| HAAs | <ul style="list-style-type: none"> • Pros <ul style="list-style-type: none"> – Capable of accessing most earth areas – With air superiority, unlimited access to areas of interest – Low impact of weather at altitude • Cons <ul style="list-style-type: none"> – No access into denied territory (peacetime) – No access to without air superiority (conflict) – Limited access to areas where atmosphere not conducive |
| HA UAVs | <ul style="list-style-type: none"> • Pros <ul style="list-style-type: none"> – Flies above the impact of weather • Cons <ul style="list-style-type: none"> – Limited by fuel range – No access to denied territory (peacetime) – No access without air superiority in conflict with peer/near-peer nations |
| MA UAVs | <ul style="list-style-type: none"> • Pros • Cons <ul style="list-style-type: none"> – Limited by fuel range – Limited by weather – No access to denied territory (peacetime) – No access without air superiority in conflict |

| Coverage | |
|----------|---|
| TacSats | <ul style="list-style-type: none"> • Pros <ul style="list-style-type: none"> – Large coverage area (due to altitude) – Payload capacity allows adequate resolution/comm capacity – Persistent coverage possible with constellation in MEO/GEO, but no planned TacSats in this belt • Cons <ul style="list-style-type: none"> – Limited time over target (LEO) – Predictable overflight can lead to target concealment – Poor look angle may affect coverage capability – Limited by cloud cover (EO) |
| HAAs | <ul style="list-style-type: none"> • Pros <ul style="list-style-type: none"> – Relatively large footprint – Higher payload capacity (sensor capability) – Near persistent coverage inside footprint (only limited by sensor) – Lower altitude than TacSat = better resolution/lower transmitter power required • Cons <ul style="list-style-type: none"> – Steep look angles at edge of footprint – Slow speed limits ability to change coverage area – Limited by cloud cover (EO) |
| HA UAVs | <ul style="list-style-type: none"> • Pros <ul style="list-style-type: none"> – Speed/ability to move coverage area – Large payload capacity – Can change altitude to increase resolution; can fly below weather if needed for ISR (EO) – Higher altitude increases footprint • Cons <ul style="list-style-type: none"> – Limited persistence may require handoff between platforms= possible loss in coverage – Payload capacity smaller than TacSat/HAA |
| MA UAVs | <ul style="list-style-type: none"> • Pros <ul style="list-style-type: none"> – Speed/ability to move coverage area – Can change altitude to increase resolution; can fly below weather if needed for ISR (EO) • Cons <ul style="list-style-type: none"> – Coverage loss may occur if handoff between platforms occurs – Smallest payload capacity – Small coverage area (due to lower operating altitude) |

| Endurance | |
|-------------|--|
| TacSats | <ul style="list-style-type: none"> • Pros <ul style="list-style-type: none"> – Less logistical reachback requirements than other platforms – Potential for increased coverage with additional platforms • Cons <ul style="list-style-type: none"> – Limited time over target for LEO – Potential coverage gaps – Requirement for several platforms for continuous coverage |
| HAAs | <ul style="list-style-type: none"> • Pros <ul style="list-style-type: none"> – Projected up to one year persistence over target area (geostationary) • Cons |
| HA UAVs | <ul style="list-style-type: none"> • Pros <ul style="list-style-type: none"> – Can offer persistence with enough platforms – Targets moving outside coverage area continue to be tracked due to platform mobility • Cons <ul style="list-style-type: none"> – Limited by fuel consumption – Requirement for multiple platforms for persistence – Maintenance intensive—most likely to require repairs (i.e., less time over target) |
| MA UAVs | <ul style="list-style-type: none"> • Pros <ul style="list-style-type: none"> – Can offer persistence with enough platforms – Targets moving outside coverage area continue to be tracked due to platform mobility • Cons <ul style="list-style-type: none"> – Large forward deployed footprint for continuous operations – Most restricted by fuel/weather – Requirement for multiple platforms for persistence – Maintenance intensive—most likely to require repairs (i.e., less time over target) |
| Flexibility | |
| TacSats | <ul style="list-style-type: none"> • Pros <ul style="list-style-type: none"> – Large payload capacity allows multi-sensor capability • Cons <ul style="list-style-type: none"> – Mission capability (ISR vs. Comm) impacted by orbit parameters (tradeoff) – Fixed capability once launched (no payload switching) – No video capability – Limited surface area=antennas close together=interference |
| HAAs | <ul style="list-style-type: none"> • Pros <ul style="list-style-type: none"> – Large payload capacity – Large surface area allows multiple antennas w/out interference – Altitude/geostationary position make good platform for ISR/comm missions • Cons <ul style="list-style-type: none"> – Stationary position makes tempting target for MJJ |
| HA UAVs | <ul style="list-style-type: none"> • Pros <ul style="list-style-type: none"> – Can provide video streaming – Can change payloads to support both ISR/comm missions • Cons <ul style="list-style-type: none"> – Limited payload capacity limits flexibility – Moving platform may cause tracking issues for wideband use – Limited comm payloads developed for this platform |
| MA UAVs | <ul style="list-style-type: none"> • Pros <ul style="list-style-type: none"> – Provides video streaming – Can change payloads quickly – Most likely platform to launch multiple vehicles to conduct multiple missions • Cons <ul style="list-style-type: none"> – Smallest payload capacity=less capability to perform multiple missions – Lower altitude causes comm tracking issues for wideband use – Limited comm payloads |

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APPENDIX B: PAIR-WISE COMPARISON SURVEY

UAS, HALE Airship, TacSat Attribute Survey

Please complete and return to jckacala@nps.edu or cmcollie@nps.edu NLT 14 AUG. Thank you for your time and participation.

Who we are: MAJ Jeff Kacala (USA) and Maj. Corey Collier (USMC) are graduate students attending the Naval Postgraduate School working toward a MS in Space Systems Operations.

Survey Purpose: To survey a group of experts to accurately weight the critical attributes of a persistent ISR/communications platform for thesis purposes.

Thesis Information:

Thesis Statement: The current DoD investment in medium altitude, high altitude, and tactical space persistent ISR and Communications platforms does not currently meet warfighter operational requirements.

Thesis Purpose: 1) To capture in one place key information relevant to persistent ISR and communications platforms and 2) To conduct a sound cost effectiveness analysis to determine the best use of future DoD research and development and procurement funds in the area of persistent ISR and communications platforms.

Thesis Scope: This thesis will bound its analysis by constraining itself to one medium altitude, high altitude, and tactical space representative platform measured against the following five attributes: responsiveness, access, coverage, endurance, and flexibility.

The following is a list of attributes to be used in our thesis and their definitions:

- 1) Responsiveness: The ability to react to new missions in a different geographical area and begin passing the user actionable data. Additionally, it is the ability to replace the asset if lost.
- 2) Access: The geographic extent of what the payload can see over time – i.e. no time limit; for example, a single satellite in polar orbit has a global access area
- 3) Coverage: An indication of how quickly the system can view the access area measured in km²/hour
- 4) Endurance: This is the continuous amount of time a platform can spend over the target area.
- 5) Flexibility: The ability to use the same asset to perform more than one mission.

Survey Directions: For each scenario, please fill in the blank with the number (between 0 and 5) of times more important one persistent ISR/communications platform attribute is over another. If you feel the two attributes are equally important use 1. If you feel that the bold **attribute** is less important than the attribute you are comparing it to then you can use a fraction (i.e. **attribute 1** is 0.5 times as important as attribute 2).

Scenario A: The United States is conducting high intensity operations without air superiority.

Responsiveness is ____ times more important than Access, is ____ time more important than Coverage, is ____ times more important than Endurance, and ____ times more important than Flexibility.

Access is ____ times more important than Coverage, is ____ times more important than Endurance, and is ____ times more important than Flexibility.

Coverage is ____ times more important than Endurance, and ____ times more important than Flexibility.

Endurance is ____ times more important than Flexibility.

Scenario B: The United States is conducting high intensity operations with air superiority.

Responsiveness is ____ times more important than Access, is ____ time more important than Coverage, is ____ times more important than Endurance, and ____ times more important than Flexibility.

Access is ____ times more important than Coverage, is ____ times more important than Endurance, and is ____ times more important than Flexibility.

Coverage is ____ times more important than Endurance, and ____ times more important than Flexibility.

Endurance is ____ times more important than Flexibility.

Scenario C: The United States is conducting low intensity operations with air superiority.

Responsiveness is ____ times more important than Access, is ____ time more important than Coverage, is ____ times more important than Endurance, and ____ times more important than Flexibility.

Access is ____ times more important than Coverage, is ____ times more important than Endurance, and is ____ times more important than Flexibility.

Coverage is ____ times more important than Endurance, and ____ times more important than Flexibility.

Endurance is ____ times more important than Flexibility.

Questions/Comments:

Did you make any assumptions when filling out the survey?

When measuring responsiveness, what numbers would be useful and/or desirable?

Does endurance need to be contiguous? Would you rather have a platform that can provide 4 straight hours of coverage or a platform that can provide 8 hours of coverage in 15 minute blocks?

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APPENDIX C: PLATFORM PARAMETRIC COMPARISON TABLE

Platform Parametric Comparison

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 |
|--|---|-----------------------------------|---|---|
| Responsiveness (Target 885 km distant) | <u>LEO</u> : 1.5 hours (best) 22 hours (worst) Average: 11.75 hours <u>HEO</u> : 0 hours (best) 24 hours (worst) Average: 12 hours | 15.8 hours | 1.4 hours | 4.1 hours |
| Access (% of Denied Territory Scenario) | 120,540 km ² = 100% | 8,793 km ² = 7.3% | 8,793 km ² = 7.3% | 3,380 km ² = 2.8% |
| Coverage (hours to provide ISR coverage of designated area) | <u>LEO</u> : 24 days = 576 hours | 24 hours | 24 hours | 72 hours |
| Endurance (# hours over 6 month period) | <u>LEO</u> : $\approx 10 \text{ min/day} \times 182 \text{ days}$ = 30.33 hours <u>HEO</u> : 7 hours/day $\times 182 \text{ days}$ = 1274 hours | 24 hrs * 182 days = 4368 hours | 4368 hours * .315 Average % Utility = 1376 hours | 4368 hours * .315 Average % Utility = 1376 hours |
| Flexibility (# number of aircraft required to perform both missions) | 3 | 1 | 2 | 2 |

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APPENDIX D: COVERAGE CALCULATION TABLE

| | Angular Radius of the Earth (rad) | Subplatform Point to Target (rad) | Earth Central Angle (rad) | Distance to Target (km) | Earth Angle between Nadir and Toe of Footprint | Length of Footprint (km) | Width of Footprint (km) | Footprint Area (km ²) |
|---------------|---|--|--|---|--|--|--|-----------------------------------|
| ISR PLATFORM | $\rho = \sin^{-1}\left(\frac{Re}{Re+H}\right)$ | $\eta = \sin^{-1}(\cos \varepsilon \sin \rho)$ | $\lambda_{HT} = 90^\circ - \varepsilon - \eta$ | $D = Re(\sin \lambda_{HT} / \sin \eta)$ | $\lambda_{\eta 0} = \cos^{-1}\left(\frac{Re}{Re+H}\right)$ | $L_f = K_L(\lambda_{\eta 0} - \lambda_{HT})$ | $W_f = Re \sin^{-1}(D \sin \theta / Re)$ | $F_A = (\pi/4) L_f W_f / \rho$ |
| Alt 1 (LEO) | 1.221461242 | 1.082078717 | 0.13965176 | 1005.53818 | 0.349335085 | 23.34185198 | 848.6329095 | 15557.68814 |
| Alt 2 | 1.492078891 | 1.21331967 | 0.008410807 | 57.26476161 | 0.078717436 | 7.826501741 | 48.18709376 | 296.2022149 |
| Alt 3 | 1.492078891 | 1.21331967 | 0.008410807 | 57.26476161 | 0.078717436 | 7.826501741 | 48.18709376 | 296.2022149 |
| Alt 4 | 1.518179584 | 1.217947776 | 0.003782701 | 25.71049274 | 0.052616743 | 5.436183242 | 21.63467513 | 92.37072385 |
| COMM PLATFORM | Angular Radius of the Earth (rad) | Nadir Angle from Subplatform | Earth Central Angle (rad) | Distance to Target (km) | Earth Angle between Nadir and Toe of Footprint | Length of Footprint (km) | Width of Footprint (km) | Footprint Area (km ²) |
| | $\rho = \sin^{-1}\left(\frac{Re}{Re+H}\right)$ | $\eta = \sin^{-1}(\cos \varepsilon \sin \rho)$ | $\lambda_{HT} = 90^\circ - \varepsilon - \eta$ | $D = Re(\sin \lambda_{HT} / \sin \eta)$ | $\lambda_{\eta 0} = \cos^{-1}\left(\frac{Re}{Re+H}\right)$ | $L_f = K_L(\lambda_{\eta 0} - \lambda_{HT})$ | $W_f = Re \sin^{-1}(D \sin \theta / Re)$ | $F_A = (\pi/4) L_f W_f / \rho$ |
| Alt 1 (HEO) | 0.349952016 | 0.328027343 | 0.893703134 | 15429.76075 | 1.220844311 | 36.41720635 | 3725.976422 | 106570.4036 |
| Alt 2 | 1.492078891 | 1.21331967 | 0.008410807 | 57.26476161 | 0.078717436 | 7.826501741 | 13.05508765 | 80.24858062 |
| Alt 3 | 1.492078891 | 1.21331967 | 0.008410807 | 57.26476161 | 0.078717436 | 7.826501741 | 13.05508765 | 80.24858062 |
| Alt 4 | 1.518179584 | 1.217947776 | 0.003782701 | 25.71049274 | 0.052616743 | 5.436183242 | 5.861415288 | 25.02571311 |
| | Assumptions: | | | | | | | |
| | (a) 20 deg platform elevation angle from the ground | | | | | | | |
| | (b) 1 deg diameter beam from ISR platforms | | | | | | | |
| | (c) 23 deg diameter beam from comm platforms | | | | | | | |
| | (d) $K_L = 111.319543$ for length in km | | | | | | | |

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APPENDIX E: ACCESS CALCULATION TABLE

| | Radius of Denied Territory (km) | Platform Altitude (km) | Platform Footprint Radius (km) | Platform Footprint Area (km ²) | New Denied Area Territory minus Platform Access (km ²) | Denied Area Platform Can Access (km ²) | Percentage of Denied Area Platform Covers |
|--|---------------------------------|------------------------|--------------------------------|--|--|--|---|
| PLATFORM | $r_1 = \sqrt{\frac{A}{\pi}}$ | | $TM_A = \frac{a}{b} = r_2$ | $P_A = (\pi/4) \frac{L_p^2}{g}$ | $A = \pi(r_1 - r_2)^2$ | | |
| Alt 1 | | | | | 120,540 | 120,540 | 100 |
| Alt 2 | 195.88 | 20 | 7,279,404,685 | 41,61803864 | 111,747 | 8,793 | 0.072943995 |
| Alt 3 | 195.88 | 20 | 7,279,404,685 | 41,61803864 | 111,747 | 8,793 | 0.072943995 |
| Alt 4 | 195.88 | 7.6 | 2,766,17378 | 6,00964478 | 117,160 | 3,380 | 0.028044094 |
| Constants: | | | | | | | |
| Total Land Mass of North Korea (km ²) | | | | 120,540 | | | |
| Viewing Angle (deg off Nadir) (Based on Worldview Metrics) | | | | 20 | | | |
| Earth Angle (rad off Nadir) (conversion) | | | | 1.221730476 | | | |
| Area of earth (km ²) | | | | 510,000,000 | | | |

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APPENDIX F: SURVEY DATABASE

| | Average Response | | | | |
|-------------------------------|------------------|-----------|-------------------|-----------|-------------------|
| Scenario A | | | | | |
| Responsiveness to Access | -1.86 | Raw Score | Normalized to 1-9 | Raw Score | Normalized to 1-9 |
| Responsiveness to Coverage | 0.29 | 0.9 | -1 | 1 | 1 |
| Responsiveness to Endurance | -1.52 | 0.7 | -3 | 2 | 3 |
| Responsiveness to Flexibility | 0.48 | 0.5 | -5 | 3 | 5 |
| Access to Coverage | 2.00 | 0.3 | -7 | 4 | 7 |
| Access to Endurance | 1.96 | 0.1 | -9 | 5 | 9 |
| Access to Flexibility | 2.57 | | | | |
| Coverage to Endurance | 0.14 | | | | |
| Coverage to Flexibility | 1.67 | | | | |
| Endurance to Flexibility | 2.95 | | | | |
| Scenario B | | | | | |
| Responsiveness to Access | 0.24 | | | | |
| Responsiveness to Coverage | 0.10 | | | | |
| Responsiveness to Endurance | -2.43 | | | | |
| Responsiveness to Flexibility | 0.57 | | | | |
| Access to Coverage | -1.43 | | | | |
| Access to Endurance | -1.81 | | | | |
| Access to Flexibility | 0.67 | | | | |
| Coverage to Endurance | -0.67 | | | | |
| Coverage to Flexibility | 1.76 | | | | |
| Endurance to Flexibility | 3.62 | | | | |
| Scenario C | | | | | |
| Responsiveness to Access | 2.05 | | | | |
| Responsiveness to Coverage | 0.52 | | | | |
| Responsiveness to Endurance | 0.14 | | | | |
| Responsiveness to Flexibility | 0.73 | | | | |
| Access to Coverage | -2.57 | | | | |
| Access to Endurance | -1.67 | | | | |
| Access to Flexibility | -0.67 | | | | |
| Coverage to Endurance | 0.38 | | | | |
| Coverage to Flexibility | -0.67 | | | | |
| Endurance to Flexibility | 1.24 | | | | |

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APPENDIX G: PLATFORM EFFECTIVENESS SCORES

| | | | | Utility = $f[X_1(R)+X_2(A)+X_3(C)+X_4(E)+X_5(F)] \times 100$ |
|-------------------------|----------------|--|--------------------------------------|--|
| LEO TacSat Scenario (A) | MOE | MOE Weights Scenario (A) From Figures 15-16 | Platform Score From Figures 23-32 | Platform Utility Score= 18.5272 |
| | Responsiveness | 0.151 | 0.122 | |
| | Access | 0.334 | 0.364 | |
| | Coverage | 0.179 | 0.074 | |
| | Endurance | 0.223 | 0.059 | |
| | Flexibility | 0.113 | 0.167 | |
| LEO TacSat Scenario (B) | MOE | MOE Weights Scenario (B) From Figures 17-18 | Platform Score From Figures 23-32 | Platform Utility Score= 9.9219 |
| | Responsiveness | 0.158 | 0.113 | |
| | Access | 0.153 | 0.200 | |
| | Coverage | 0.228 | 0.051 | |
| | Endurance | 0.331 | 0.077 | |
| | Flexibility | 0.130 | 0.105 | |
| LEO TacSat Scenario (C) | MOE | MOE Weights Scenario (C) From Figures 19-20 | Platform Score From Figures 23-32 | Platform Utility Score= 9.6972 |
| | Responsiveness | 0.224 | 0.117 | |
| | Access | 0.128 | 0.200 | |
| | Coverage | 0.237 | 0.053 | |
| | Endurance | 0.223 | 0.057 | |
| | Flexibility | 0.189 | 0.105 | |
| | | | | Platform Utility Avg 12.7154 |

| | | | | Utility = $f[X_1(R)+X_2(A)+X_3(C)+X_4(E)+X_5(F)] \times 100$ |
|-------------------------|----------------|--|--------------------------------------|--|
| HEO TacSat Scenario (A) | MOE | MOE Weights Scenario (A) From Figures 15-16 | Platform Score From Figures 23-32 | Platform Utility Score= 21.8776 |
| | Responsiveness | 0.151 | 0.122 | |
| | Access | 0.334 | 0.364 | |
| | Coverage | 0.179 | 0.164 | |
| | Endurance | 0.223 | 0.137 | |
| | Flexibility | 0.113 | 0.167 | |
| HEO TacSat Scenario (B) | MOE | MOE Weights Scenario (B) From Figures 17-18 | Platform Score From Figures 23-32 | Platform Utility Score= 13.4818 |
| | Responsiveness | 0.158 | 0.113 | |
| | Access | 0.153 | 0.200 | |
| | Coverage | 0.228 | 0.136 | |
| | Endurance | 0.331 | 0.126 | |
| | Flexibility | 0.130 | 0.105 | |
| HEO TacSat Scenario (C) | MOE | MOE Weights Scenario (C) From Figures 19-20 | Platform Score From Figures 23-32 | Platform Utility Score= 16.5280 |
| | Responsiveness | 0.224 | 0.117 | |
| | Access | 0.128 | 0.200 | |
| | Coverage | 0.237 | 0.281 | |
| | Endurance | 0.223 | 0.121 | |
| | Flexibility | 0.189 | 0.105 | |
| | | | | Platform Utility Avg 17.2958 |

| | | | | | |
|-------------------------|----------------|--|--|--------------------------------|--|
| | | | | | $Utility = f \left[X_1(R) + X_2(A) + X_3(C) + X_4(E) + X_5(F) \right] \times 100$ |
| HAA Scenario (A) | MOE | MOE Weights Scenario (A) From Figures 15-16 | Platform Score From Figures 23-32 | Platform Utility Score= | 21.8887 |
| | Responsiveness | 0.151 | 0.066 | | |
| | Access | 0.334 | 0.109 | | |
| | Coverage | 0.179 | 0.249 | | |
| | Endurance | 0.223 | 0.405 | | |
| | Flexibility | 0.113 | 0.333 | | |
| HAA Scenario (B) | MOE | MOE Weights Scenario (B) From Figures 17-18 | Platform Score From Figures 23-32 | Platform Utility Score= | 31.6424 |
| | Responsiveness | 0.158 | 0.076 | | |
| | Access | 0.153 | 0.200 | | |
| | Coverage | 0.228 | 0.303 | | |
| | Endurance | 0.331 | 0.452 | | |
| | Flexibility | 0.130 | 0.424 | | |
| HAA Scenario (C) | MOE | MOE Weights Scenario (C) From Figures 19-20 | Platform Score From Figures 23-32 | Platform Utility Score= | 28.8239 |
| | Responsiveness | 0.224 | 0.092 | | |
| | Access | 0.128 | 0.200 | | |
| | Coverage | 0.237 | 0.252 | | |
| | Endurance | 0.223 | 0.458 | | |
| | Flexibility | 0.189 | 0.424 | | |
| | | | | Platform Utility Avg | 27.4517 |

| | | | | | |
|----------------------------|----------------|--|--|--------------------------------|--|
| | | | | | $Utility = f \left[X_1(R) + X_2(A) + X_3(C) + X_4(E) + X_5(F) \right] \times 100$ |
| HA UAV Scenario (A) | MOE | MOE Weights Scenario (A) From Figures 15-16 | Platform Score From Figures 23-32 | Platform Utility Score= | 20.5445 |
| | Responsiveness | 0.151 | 0.270 | | |
| | Access | 0.334 | 0.109 | | |
| | Coverage | 0.179 | 0.362 | | |
| | Endurance | 0.223 | 0.200 | | |
| | Flexibility | 0.113 | 0.167 | | |
| HA UAV Scenario (B) | MOE | MOE Weights Scenario (B) From Figures 17-18 | Platform Score From Figures 23-32 | Platform Utility Score= | 24.5506 |
| | Responsiveness | 0.158 | 0.272 | | |
| | Access | 0.153 | 0.200 | | |
| | Coverage | 0.228 | 0.371 | | |
| | Endurance | 0.331 | 0.192 | | |
| | Flexibility | 0.130 | 0.183 | | |
| HA UAV Scenario (C) | MOE | MOE Weights Scenario (C) From Figures 19-20 | Platform Score From Figures 23-32 | Platform Utility Score= | 23.1737 |
| | Responsiveness | 0.224 | 0.261 | | |
| | Access | 0.128 | 0.200 | | |
| | Coverage | 0.237 | 0.297 | | |
| | Endurance | 0.223 | 0.191 | | |
| | Flexibility | 0.189 | 0.183 | | |
| | | | | Platform Utility Avg | 22.7563 |

| | | | | | |
|---------------------|----------------|--|--------------------------------------|--|---------|
| | | | | Utility = $f[X_1(R)+X_2(A)+X_3(C)+X_4(E)+X_5(F)] \times 100$ | |
| MA UAV Scenario (A) | MOE | MOE Weights Scenario (A) From Figures 15-16 | Platform Score From Figures 23-32 | Platform Utility Score= | 18.9315 |
| | Responsiveness | 0.151 | 0.421 | | |
| | Access | 0.334 | 0.053 | | |
| | Coverage | 0.179 | 0.249 | | |
| | Endurance | 0.223 | 0.200 | | |
| | Flexibility | 0.113 | 0.167 | | |
| MA UAV Scenario (B) | MOE | MOE Weights Scenario (B) From Figures 17-18 | Platform Score From Figures 23-32 | Platform Utility Score= | 20.3632 |
| | Responsiveness | 0.158 | 0.427 | | |
| | Access | 0.153 | 0.200 | | |
| | Coverage | 0.228 | 0.138 | | |
| | Endurance | 0.331 | 0.152 | | |
| | Flexibility | 0.130 | 0.183 | | |
| MA UAV Scenario (C) | MOE | MOE Weights Scenario (C) From Figures 19-20 | Platform Score From Figures 23-32 | Platform Utility Score= | 21.8949 |
| | Responsiveness | 0.224 | 0.413 | | |
| | Access | 0.128 | 0.200 | | |
| | Coverage | 0.237 | 0.117 | | |
| | Endurance | 0.223 | 0.172 | | |
| | Flexibility | 0.189 | 0.183 | | |
| | | | | Platform Utility Avg | 20.3965 |

Utility Score is for (1) Platform; Effectiveness Score is dependent on the number and type of platforms in the Alternative.

| Alternative Effectiveness Score | |
|---------------------------------|---|
| Alternative 1 | 1403.08 |
| All LEO TacSat | Alternative 1 Effectiveness Score = (# LEO TacSats) X (LEO TacSat Avg Util. Score) |
| Alternative 2 | 1908.50 |
| All HEO TacSat | Alternative 2 Effectiveness Score = (# HEO TacSats) X (HEO TacSat Avg Util. Score) |
| Alternative 3 | 5270.72 |
| All HAA | Alternative 3 Effectiveness Score = (# HAAs) X (HAA Avg Util. Score) |
| Alternative 4 | 1227.30 |
| All HA UAV | Alternative 4 Effectiveness Score = (# HA UAVs) X (HA UAV Avg Util. Score) |
| Alternative 5 | 18299.70 |
| All MA UAV | Alternative 5 Effectiveness Score = (# MA UAVs) X (MA UAV Avg Util. Score) |
| Alternative 6 | 4975.88 |
| Scenario A | Alternative 6 Effectiveness Score = ((#LEO TacSats)(LEO TacSat Scen A Util Score))+((#HEO TacSats)(HEO TacSat Scen A Util Score))+((#HAAs)(HAA Scen A Util Score))+((#HA UAVs)(HA UAV Scen A Util Score))+((#MA UAVs)(MA UAV Scen A Util Score)) |
| Alternative 7 | 6292.38 |
| Scenario B | Alternative 7 Effectiveness Score = ((#LEO TacSats)(LEO TacSat Scen B Util Score))+((#HEO TacSats)(HEO TacSat Scen B Util Score))+((#HAAs)(HAA Scen B Util Score))+((#HA UAVs)(HA UAV Scen B Util Score))+((#MA UAVs)(MA UAV Scen B Util Score)) |
| Alternative 8 | 6589.31 |
| Scenario C | Alternative 8 Effectiveness Score = ((#LEO TacSats)(LEO TacSat Scen C Util Score))+ ((#HEO TacSats)(HEO TacSat Scen C Util Score))+((#HAAs)(HAA Scen C Util Score))+((#HA UAVs)(HA UAV Scen C Util Score))+((#MA UAVs)(MA UAV Scen C Util Score)) |

| | |
|-----------------------------|--|
| Alternative 9 | 5854.48 |
| All Scenarios Equal | Alternative 9 Effectiveness Score = ((#LEO TacSats)(LEO TacSat Avg Util Score)) + ((#HEO TacSats)(HEO TacSat Avg Util Score)) + ((#HAAs)(HAA Avg Util Score)) + ((#HA UAVs)(HA UAV Avg Util Score)) + ((#MA UAVs)(MA UAV Avg Util Score)) |
| Alternative 10 | 5612.33 |
| Scenario A Weighted Highest | Alternative 10 Effectiveness Score = ((#LEO TacSats)(LEO TacSat Avg Util Score)) + ((#HEO TacSats)(HEO TacSat Avg Util Score)) + ((#HAAs)(HAA Avg Util Score)) + ((#HA UAVs)(HA UAV Avg Util Score)) + ((#MA UAVs)(MA UAV Avg Util Score)) |
| Alternative 11 | 5946.44 |
| Scenario B Weighted Highest | Alternative 11 Effectiveness Score = ((#LEO TacSats)(LEO TacSat Avg Util Score)) + ((#HEO TacSats)(HEO TacSat Avg Util Score)) + ((#HAAs)(HAA Avg Util Score)) + ((#HA UAVs)(HA UAV Avg Util Score)) + ((#MA UAVs)(MA UAV Avg Util Score)) |
| Alternative 12 | 6012.39 |
| Scenario C Weighted Highest | Alternative 12 Effectiveness Score = ((#LEO TacSats)(LEO TacSat Avg Util Score)) + ((#HEO TacSats)(HEO TacSat Avg Util Score)) + ((#HAAs)(HAA Avg Util Score)) + ((#HA UAVs)(HA UAV Avg Util Score)) + ((#MA UAVs)(MA UAV Avg Util Score)) |
| Alternative 13 | 5621.86 |
| Equal Shares of Budget 1 | Alternative 13 Effectiveness Score = ((#LEO TacSats with 20% of budget 1) X (LEO TacSat Avg Util Score)) + ((#HEO TacSats with 20% of budget 1) X (HEO TacSat Avg Util Score)) + ((#HAAs with 20% of budget 1) X (HAA Avg Util Score)) + ((#HA UAVs with 20% of budget 1) X (HA UAV Avg Util Score)) + ((#MA UAVs with 20% of budget 1) X (MA UAV Avg Util Score)) |
| Alternative 14 | 2810.93 |
| Equal Shares of Budget 2 | Alternative 14 Effectiveness Score = ((#LEO TacSats with 20% of budget 2) X (LEO TacSat Avg Util Score)) + ((#HEO TacSats with 20% of budget 2) X (HEO TacSat Avg Util Score)) + ((#HAAs with 20% of budget 2) X (HAA Avg Util Score)) + ((#HA UAVs with 20% of budget 2) X (HA UAV Avg Util Score)) + ((#MA UAVs with 20% of budget 2) X (MA UAV Avg Util Score)) |
| Alternative 15 | 585.61 |
| Equal Shares of Budget 3 | Alternative 15 Effectiveness Score = ((#LEO TacSats with 20% of budget 3) X (LEO TacSat Avg Util Score)) + ((#HEO TacSats with 20% of budget 3) X (HEO TacSat Avg Util Score)) + ((#HAAs with 20% of budget 3) X (HAA Avg Util Score)) + ((#HA UAVs with 20% of budget 3) X (HA UAV Avg Util Score)) + ((#MA UAVs with 20% of budget 3) X (MA UAV Avg Util Score)) |

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